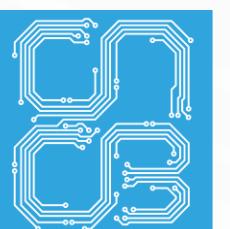


Spatio-temporal control of neural activity through gain modulation in cortical motor circuit models

Jake Stroud
Computational and Biological Learning lab
University of Cambridge, UK



**Life Sciences Interface
Doctoral Training Centre**



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Spatio-temporal control of neural activity through gain modulation in cortical motor circuit models



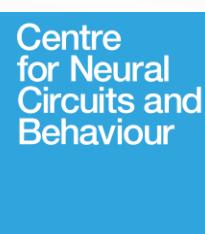
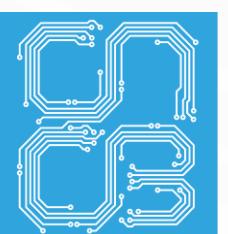
Tim Vogels



Mason Porter



Guillaume Hennequin



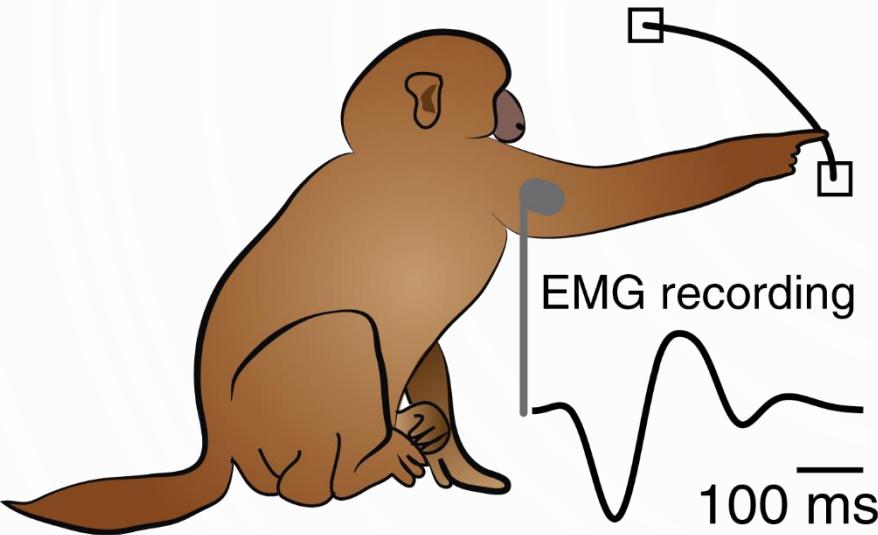
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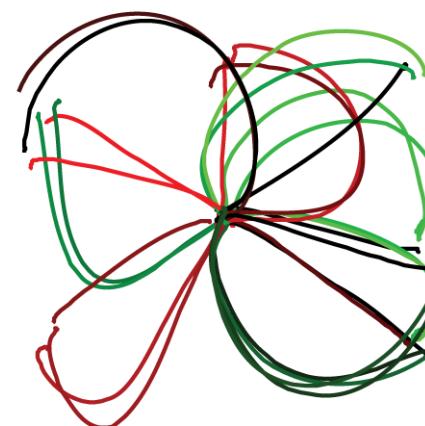
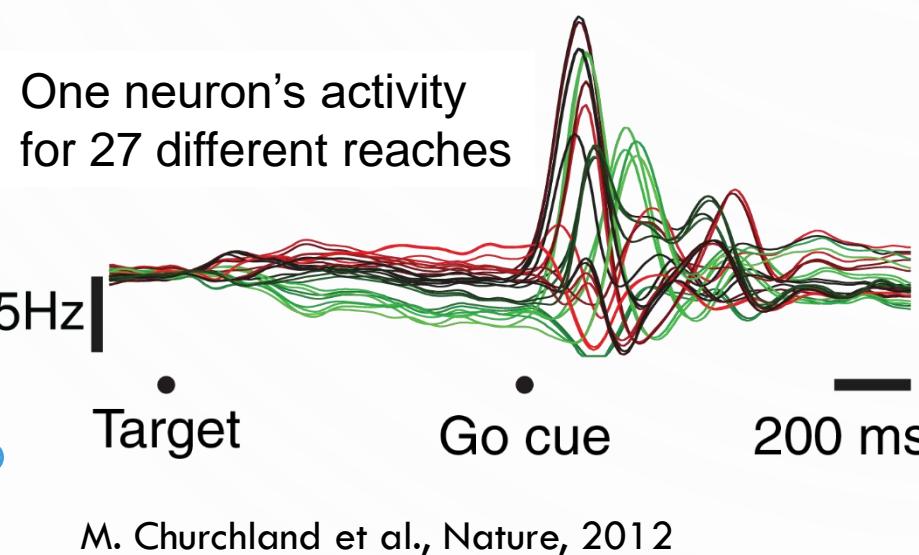
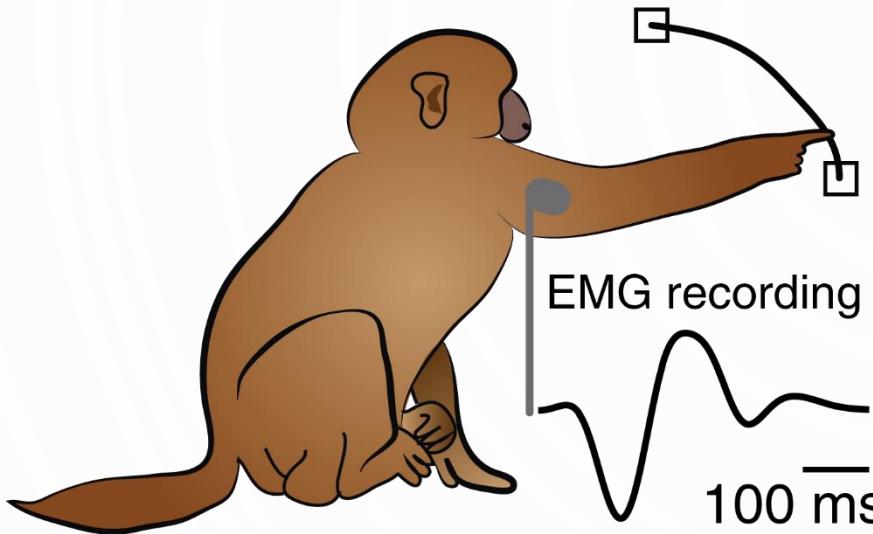
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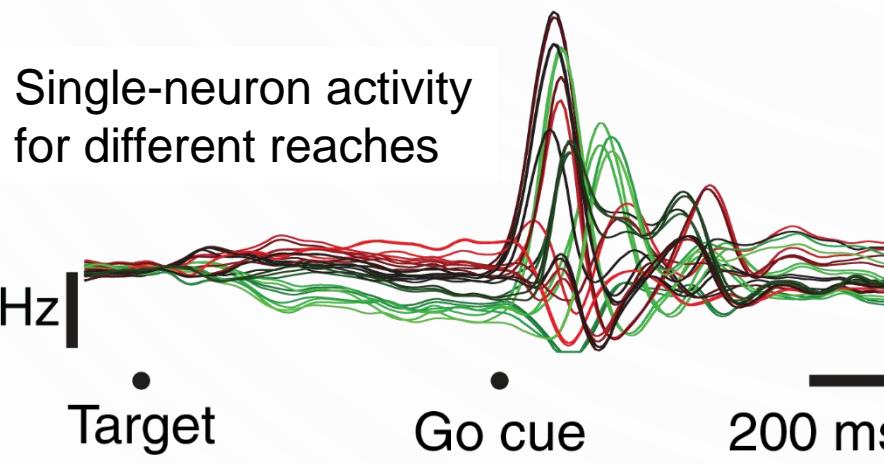
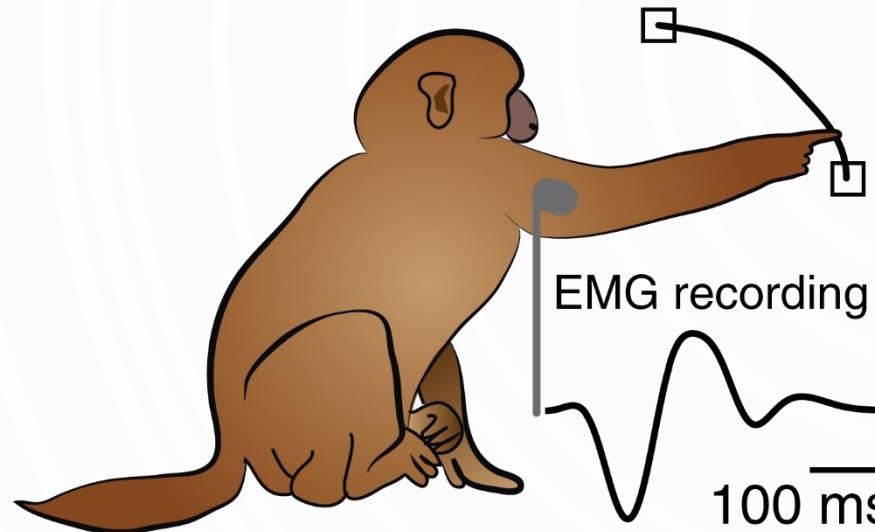
How does motor cortex generate muscle activity?



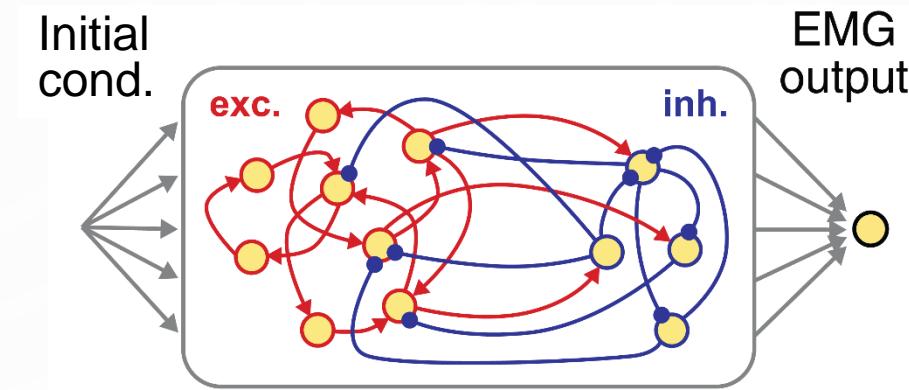
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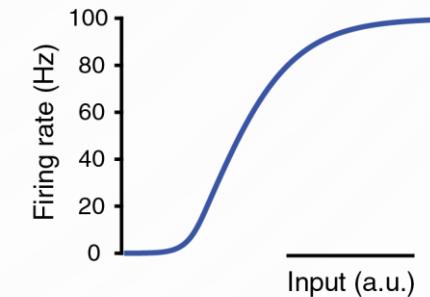
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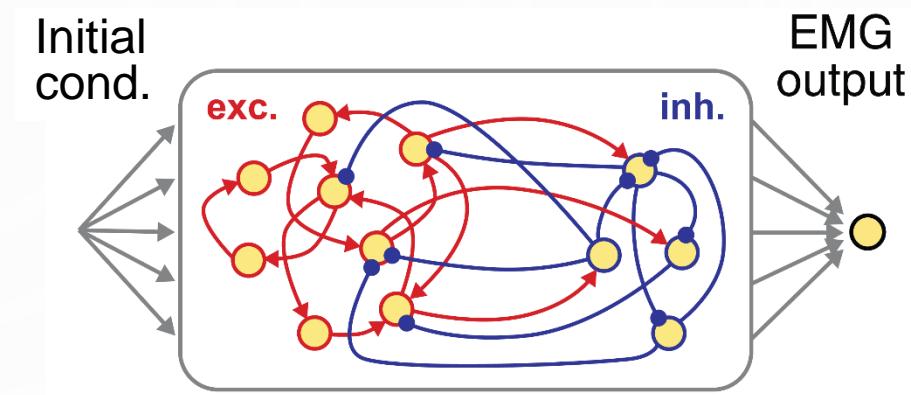
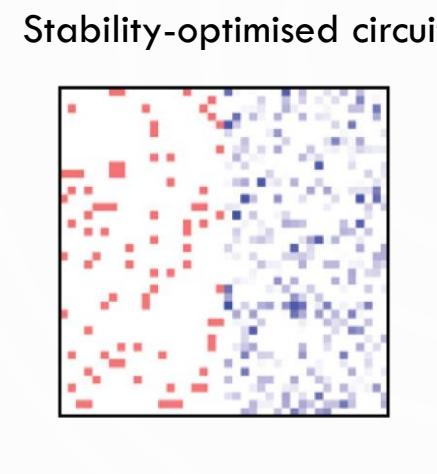
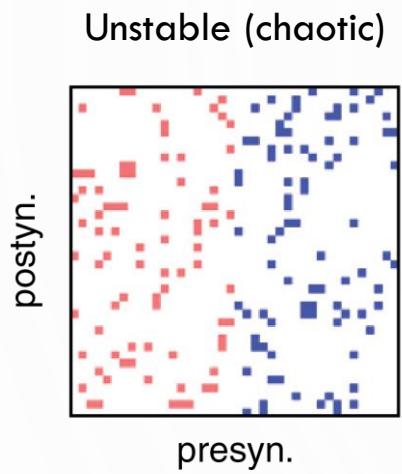
M. Churchland et al., Nature, 2012



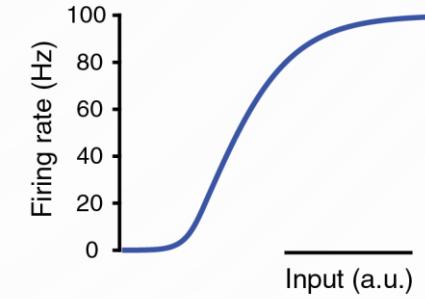
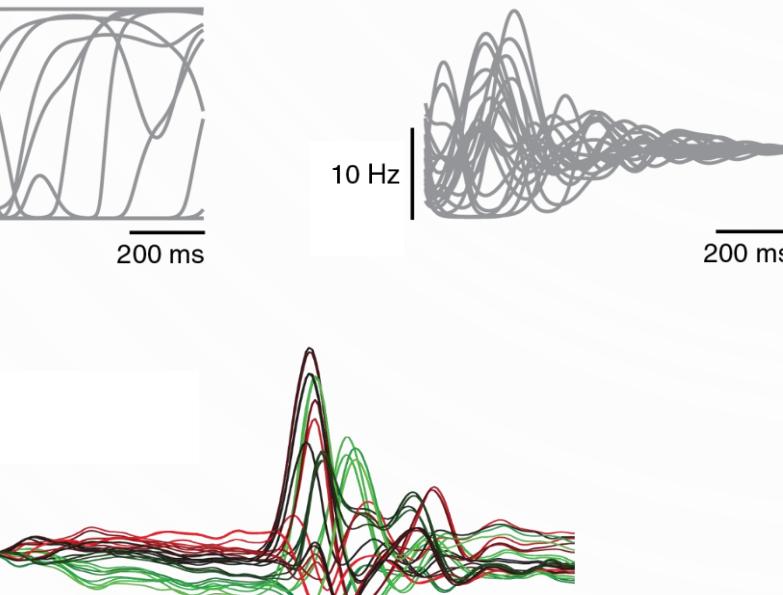
$$\tau \frac{dx}{dt} = -x + W f(x)$$



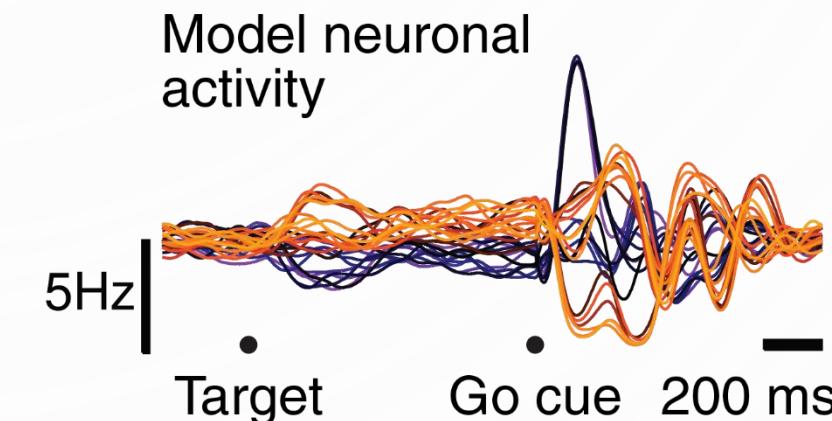
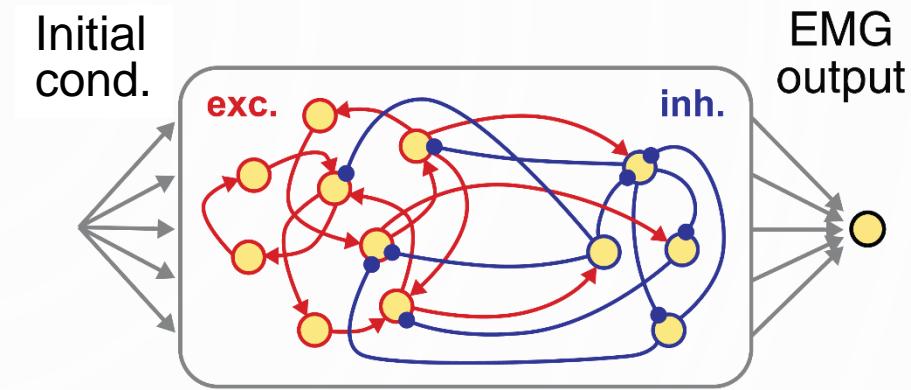
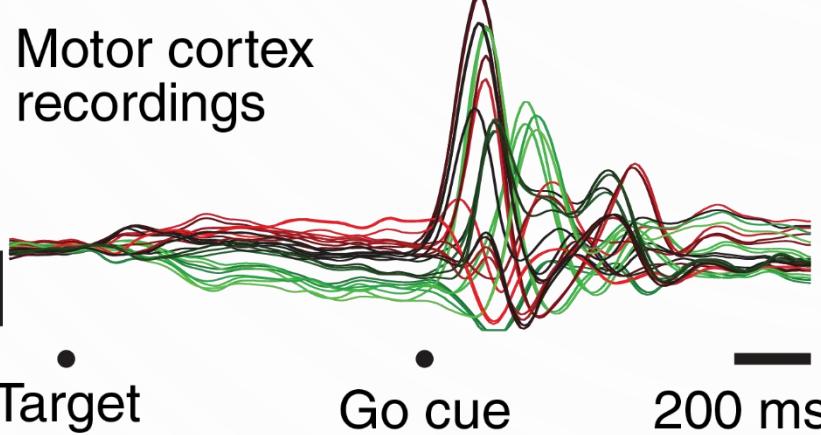
Recurrent neuronal networks



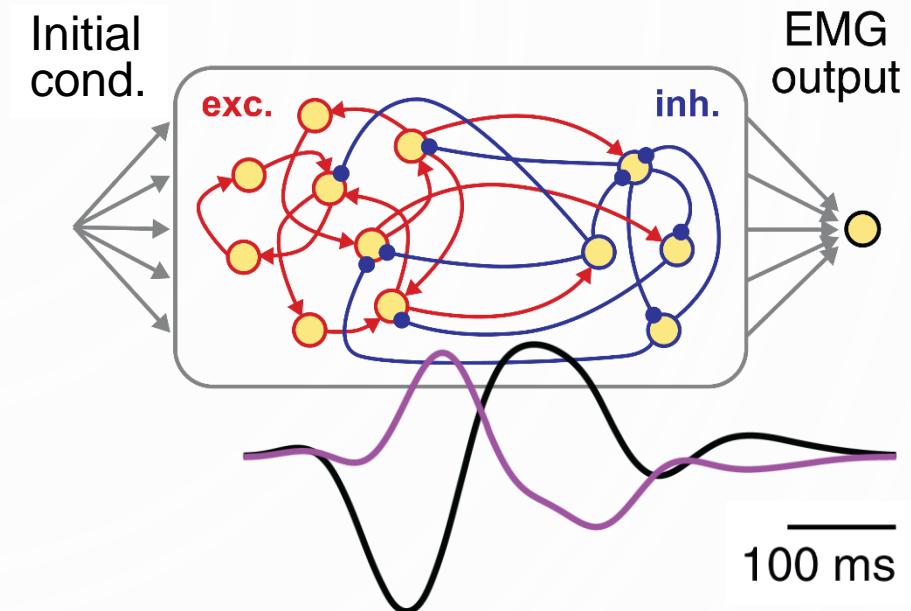
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Modelling motor cortex

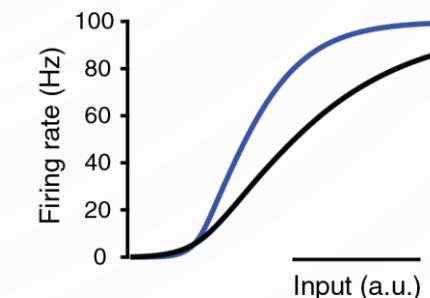


Learning new patterns of activity



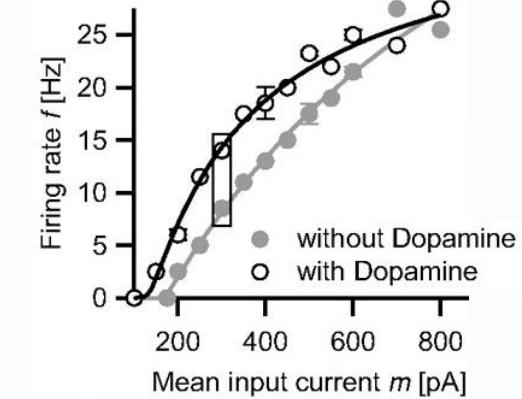
$$\tau \frac{dx}{dt} = -x + W f(x)$$

Gain function



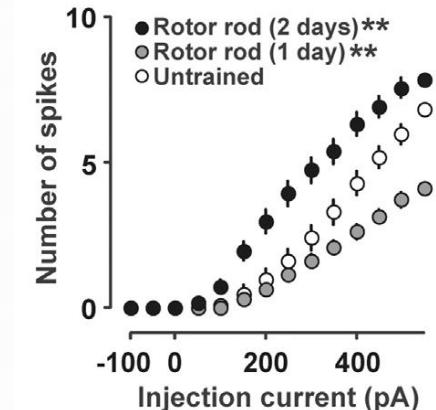
Mechanisms of gain modulation

- Background synaptic inputs or neuromodulators (e.g., dopamine) can act as a gain control signals.



Thurley et al., J. Neurophys., 2008

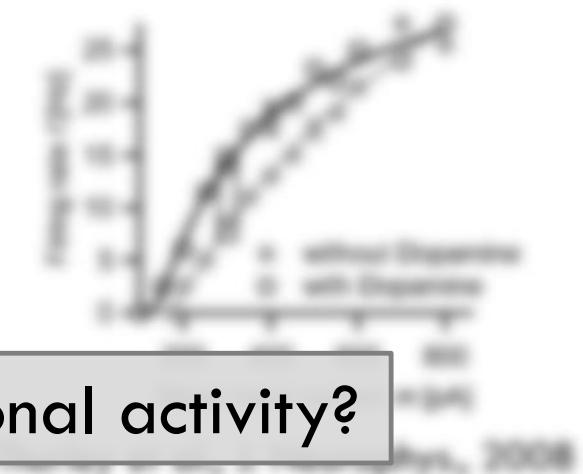
- Neural gain changes have been observed in motor cortex and spinal cord motoneurons during motor learning and movement control.



Kida and Mitsushima, Neurosci. Res., 2018

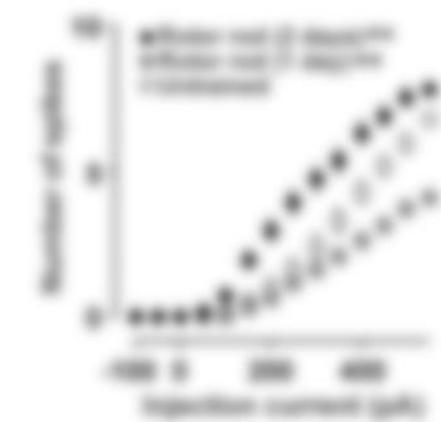
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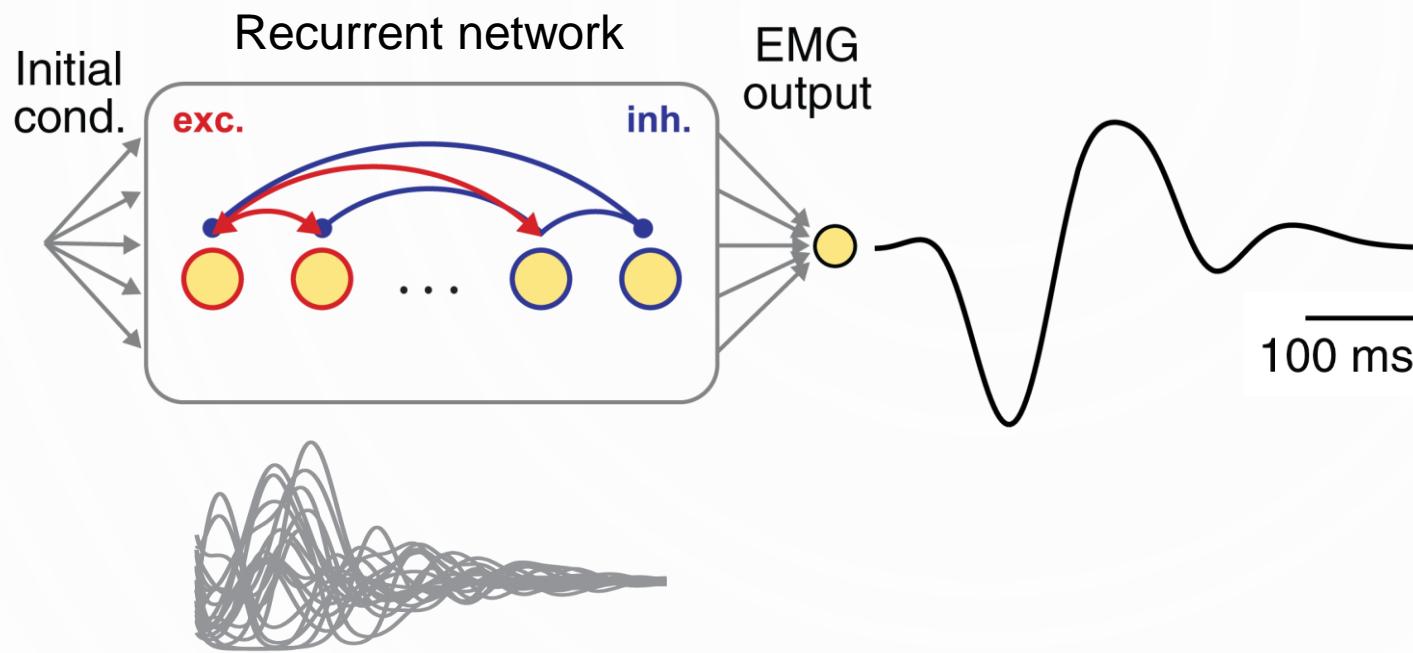


How does gain modulation affect recurrent neuronal activity?

- Neural gain changes observed motor cortex and spinal cord motoneurons during motor learning and movement control.

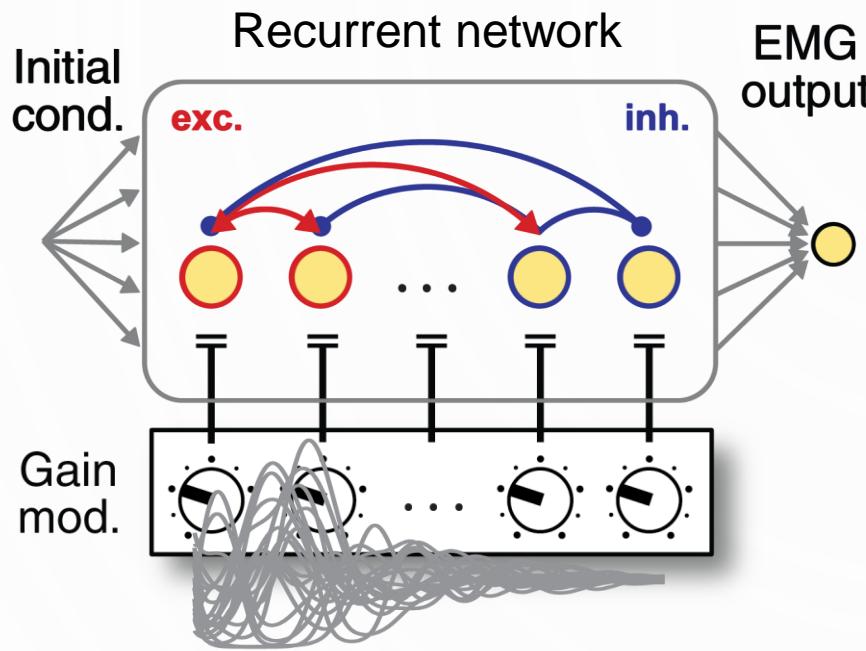


Model setup

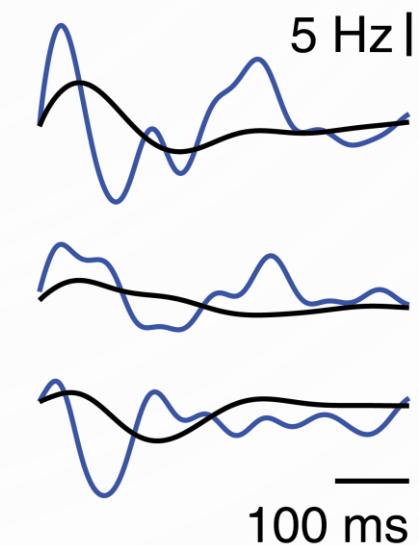
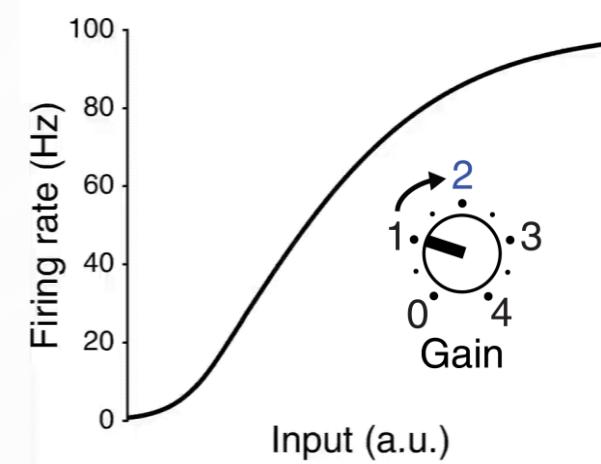


$$\tau \frac{dx}{dt} = -x + W f(x)$$

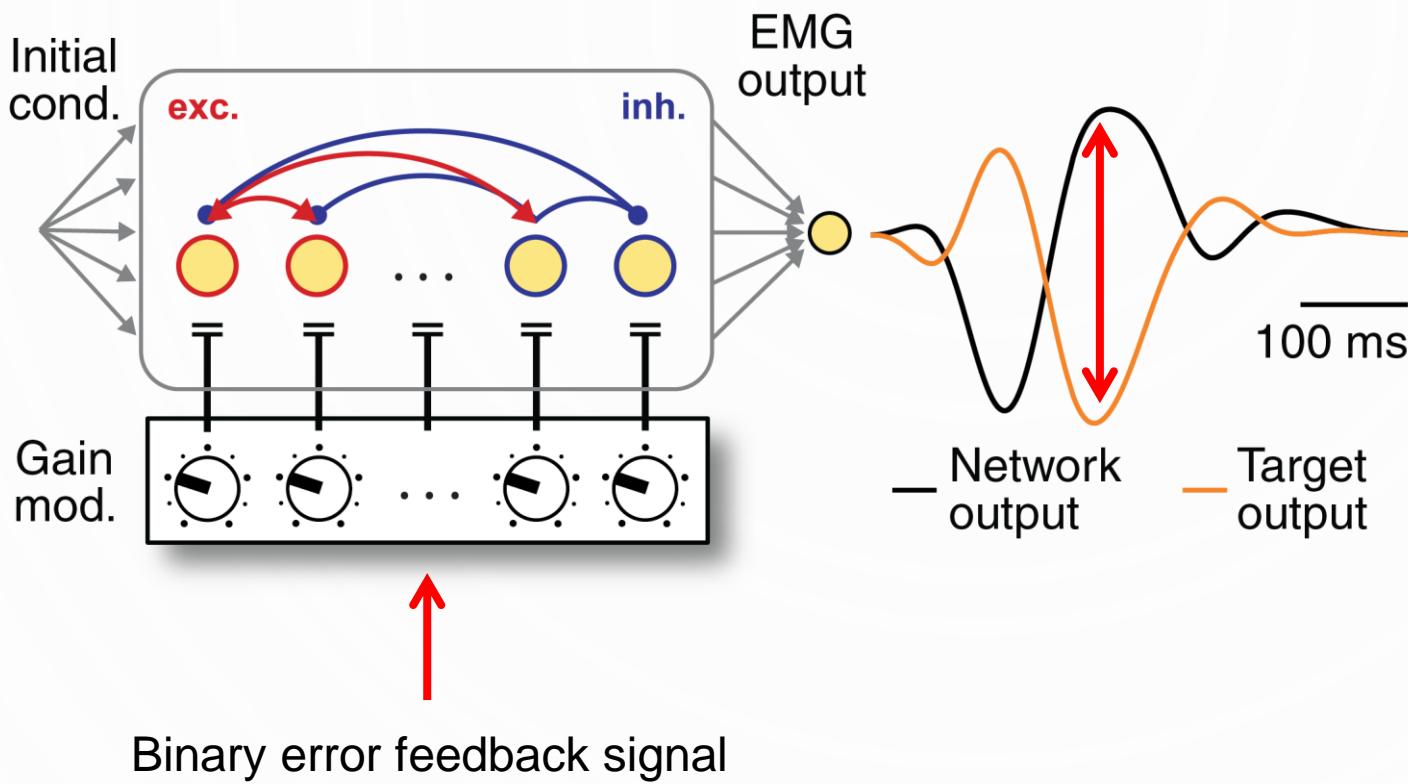
Model setup



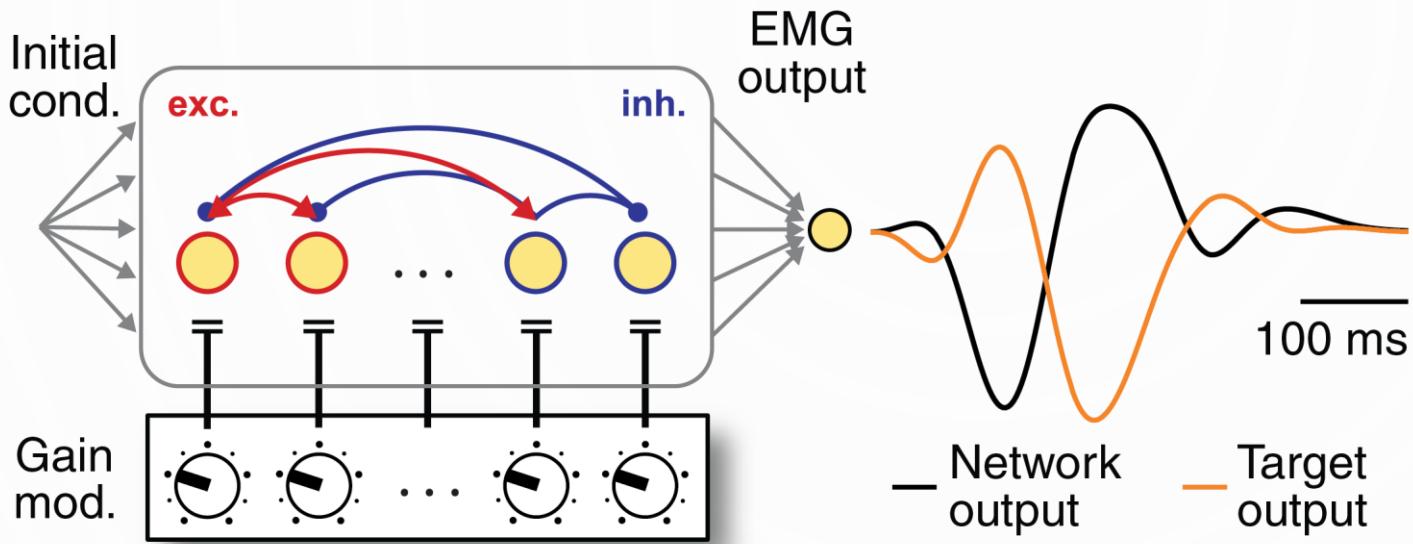
$$\tau \frac{dx}{dt} = -x + W f(g * x)$$



Learning new movements via gain modulation



Learning new movements via gain modulation



$$g_i(t_n) = g_i(t_{n-1}) + R(t_{n-1})(g_i(t_{n-1}) - \bar{g}_i(t_{n-1})) + \text{noise},$$

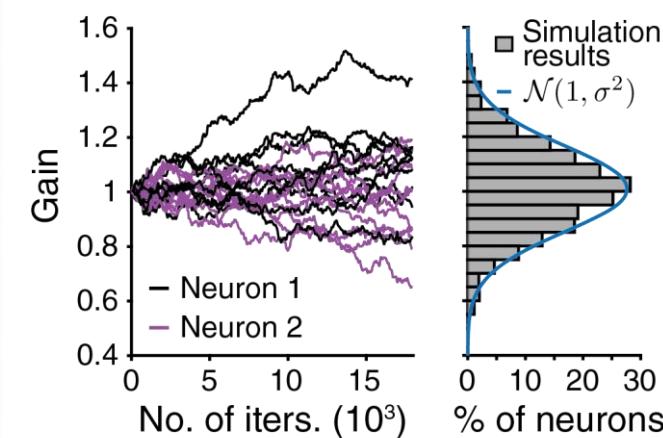
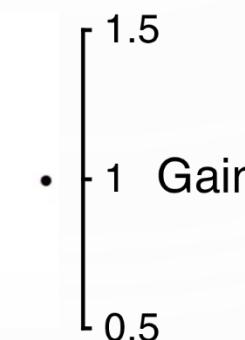
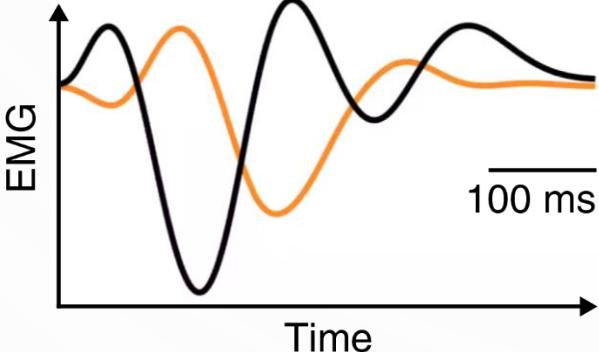
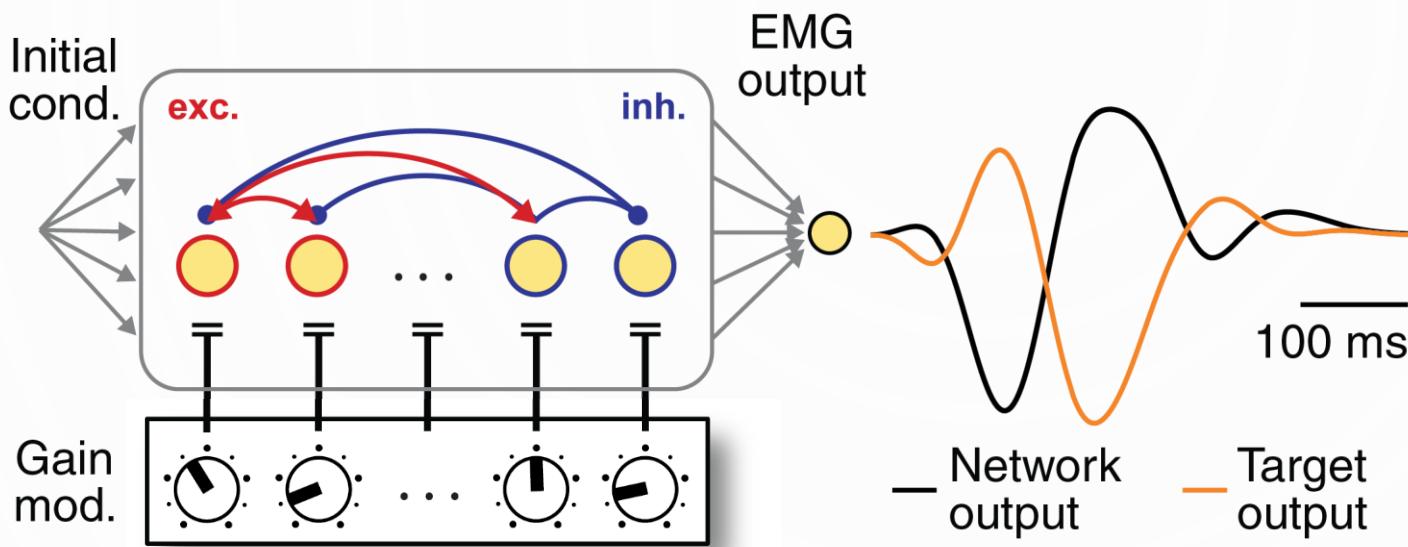
where

$$R(t_n) = \text{sgn}(\bar{\epsilon}(t_{n-1}) - \epsilon(t_n)), \quad \longleftarrow \text{Modulatory signal}$$

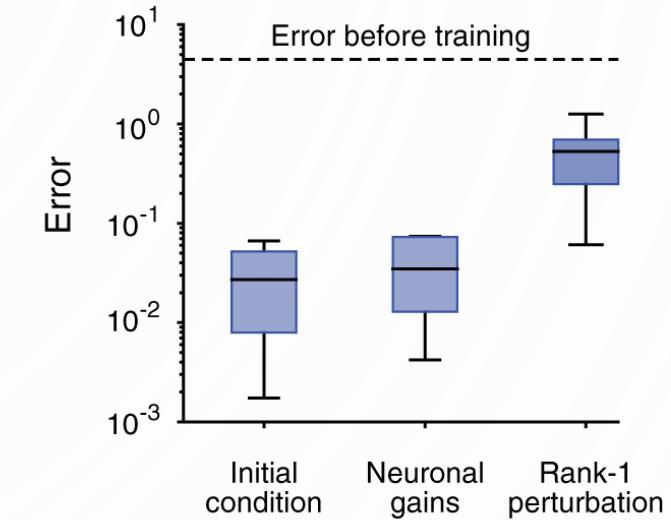
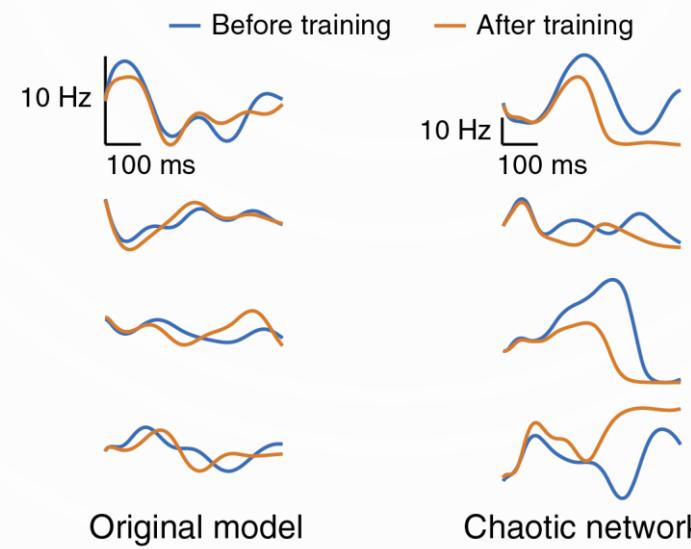
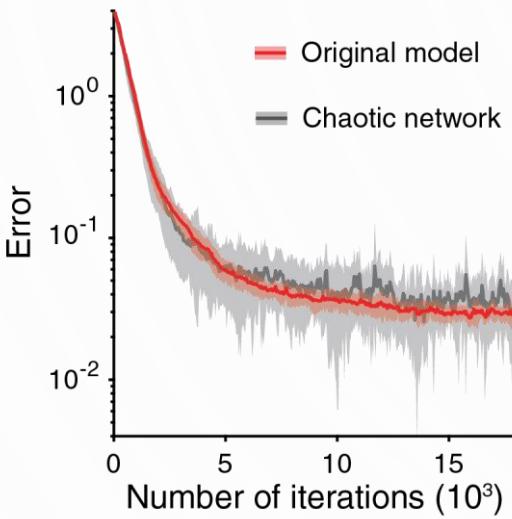
$$\bar{\epsilon}(t_n) = \alpha \bar{\epsilon}(t_{n-1}) + (1 - \alpha) \epsilon(t_n), \quad \longleftarrow \text{Low-pass filter of errors}$$

$$\bar{g}_i(t_n) = \alpha \bar{g}_i(t_{n-1}) + (1 - \alpha) g_i(t_n). \quad \longleftarrow \text{Low-pass filter of gains}$$

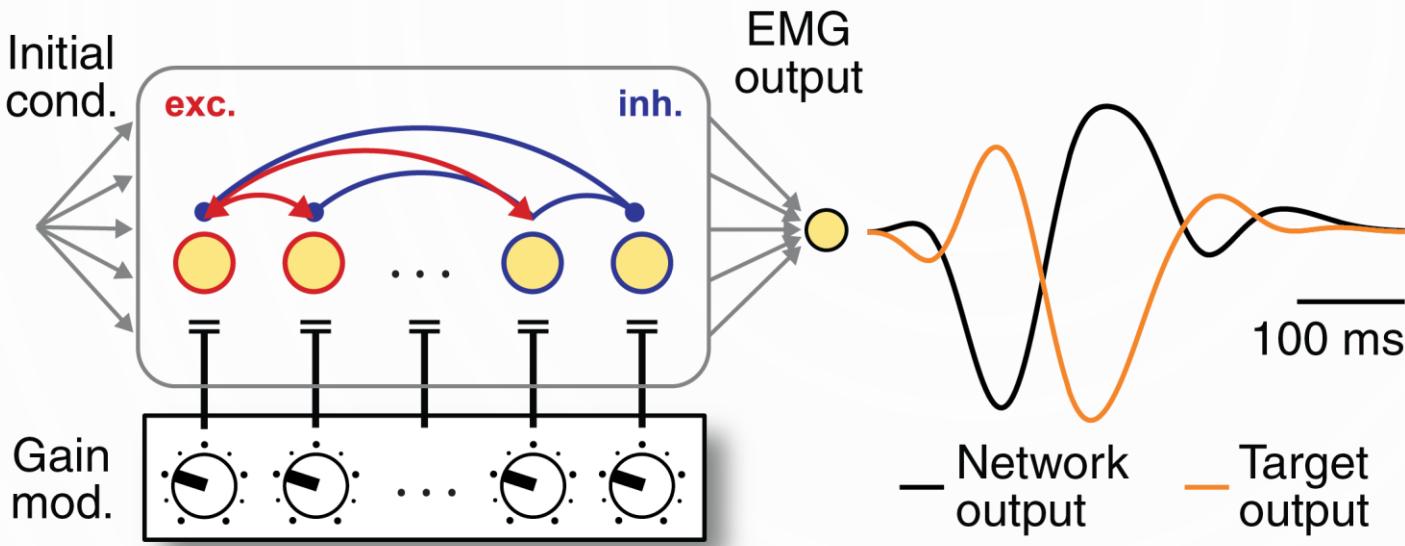
Learning new movements via gain modulation



Learning new movements via gain modulation

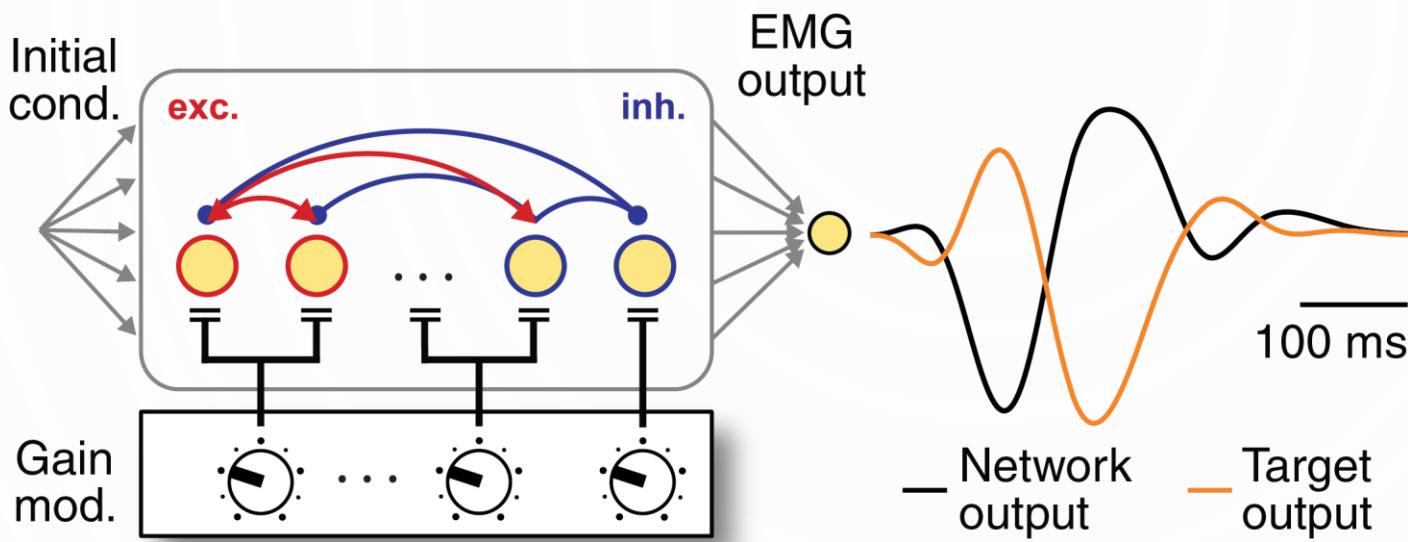


Learning new movements via gain modulation

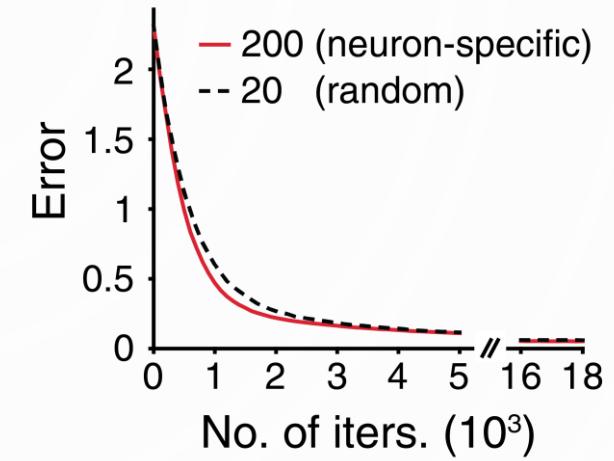
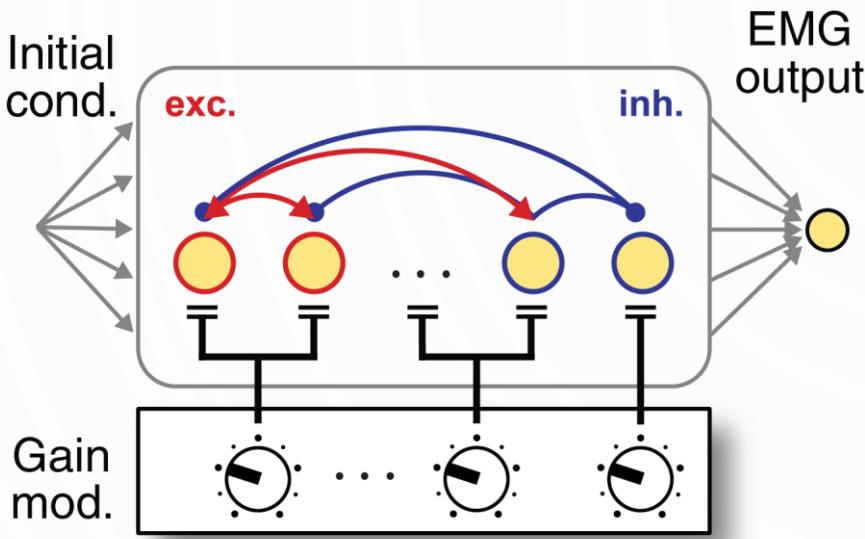


Individually modulating the gain of every neuron is likely unrealistic.

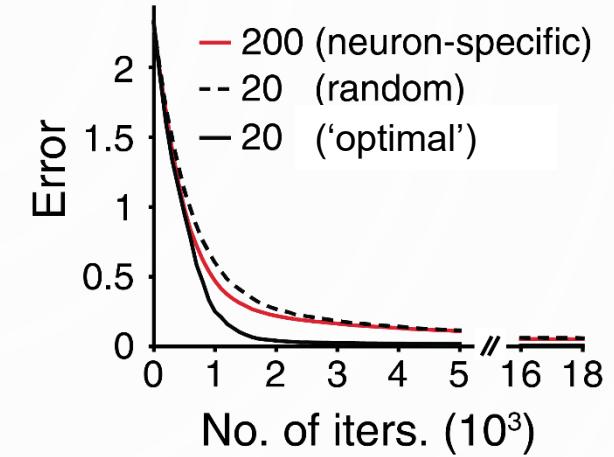
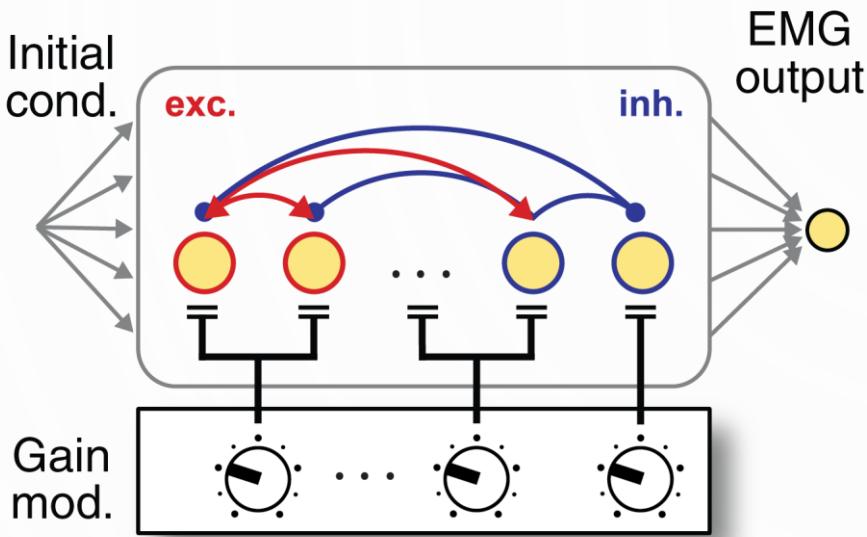
Learning through coarse, grouped modulation



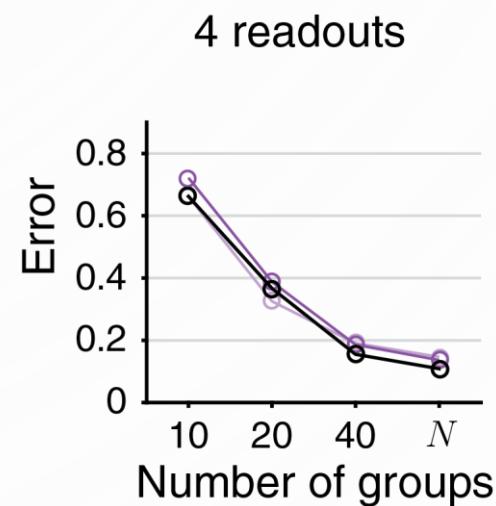
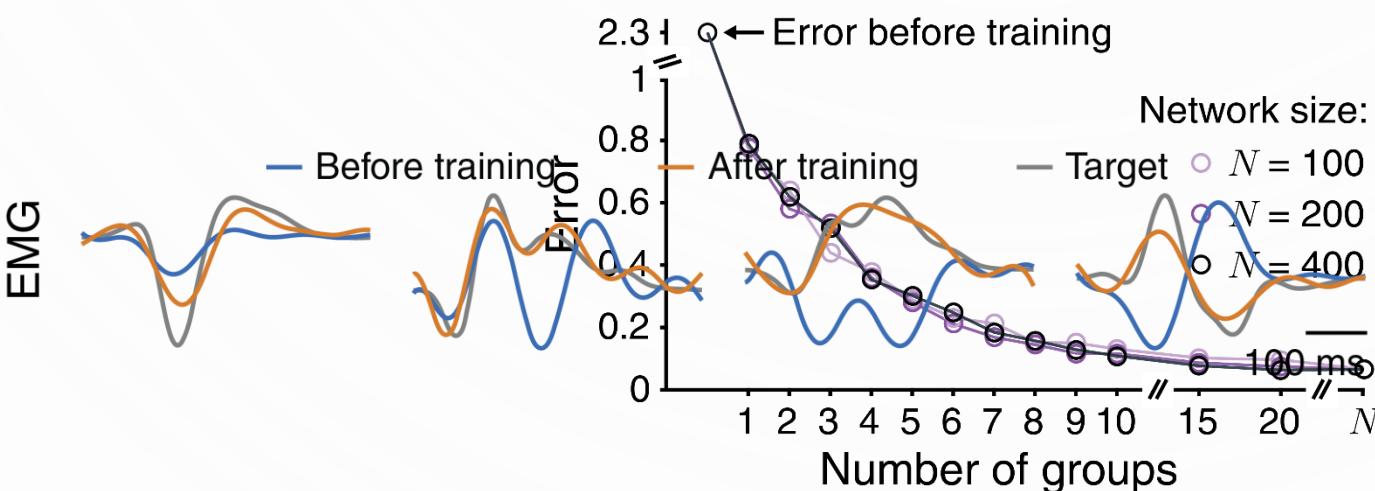
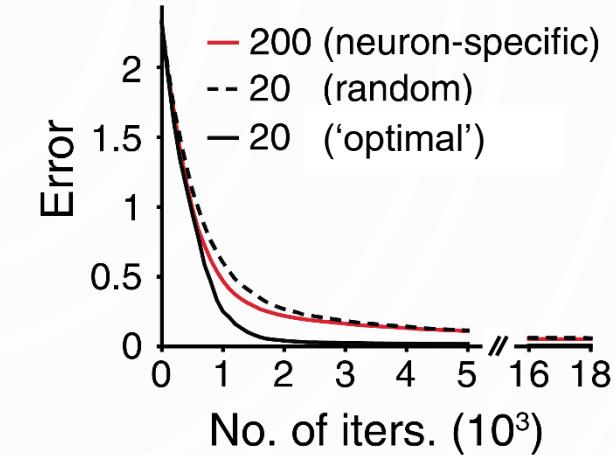
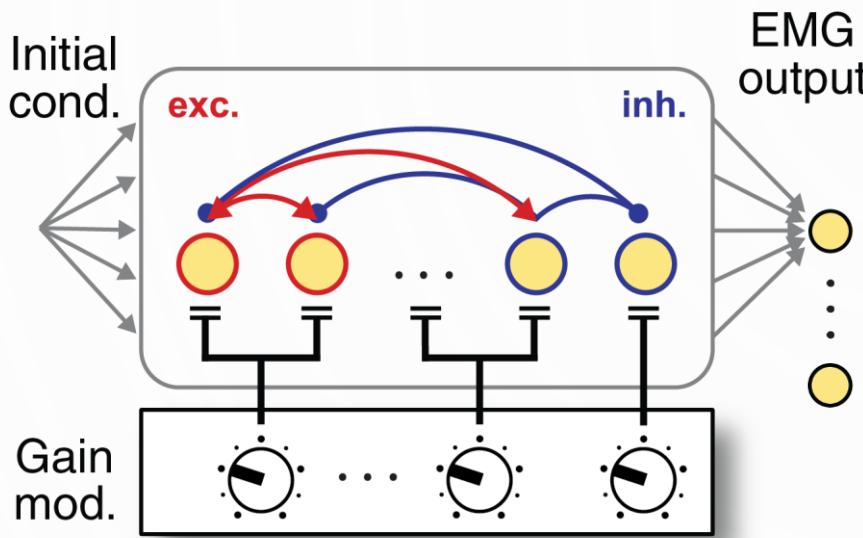
Learning through coarse, grouped modulation

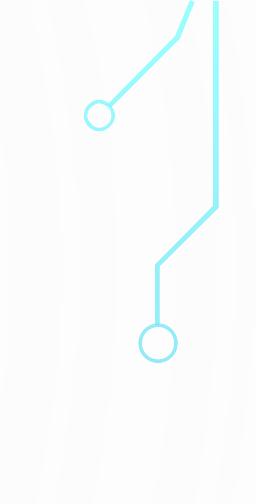
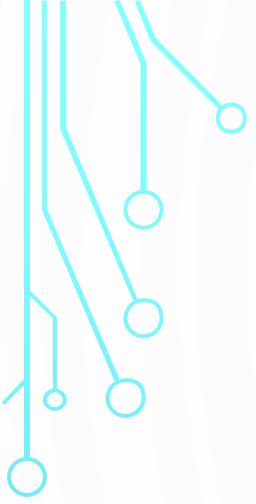


Learning through coarse, grouped modulation



Learning through coarse, grouped modulation



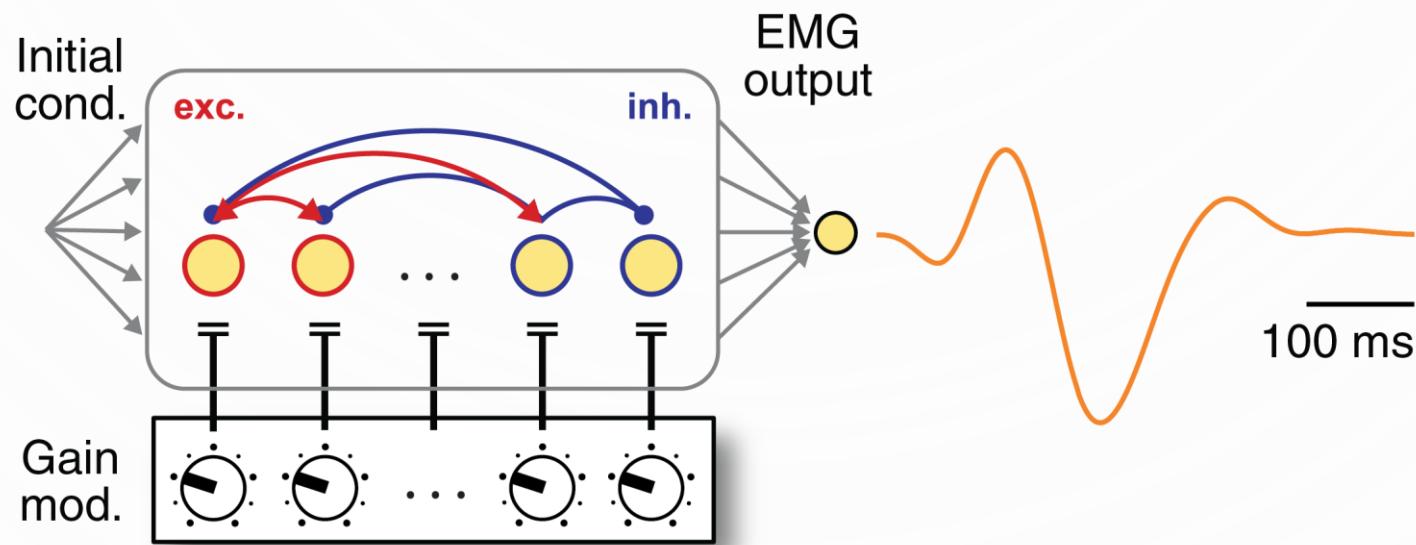


What I have shown so far



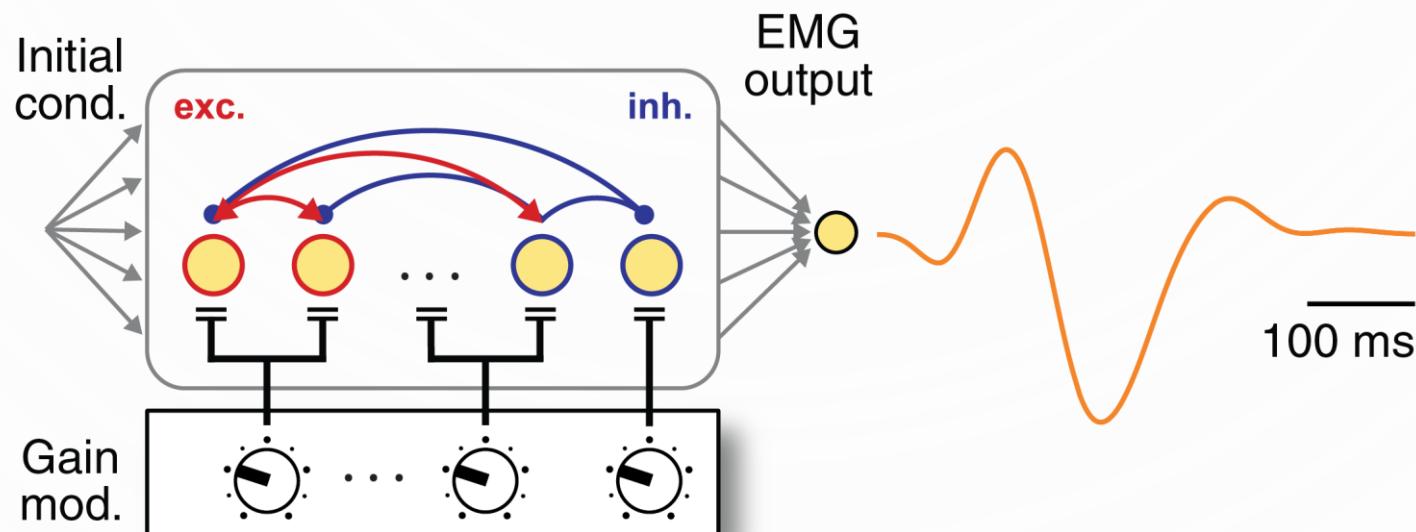
What I have shown so far

- We can learn gain patterns that generate target output activity.



What I have shown so far

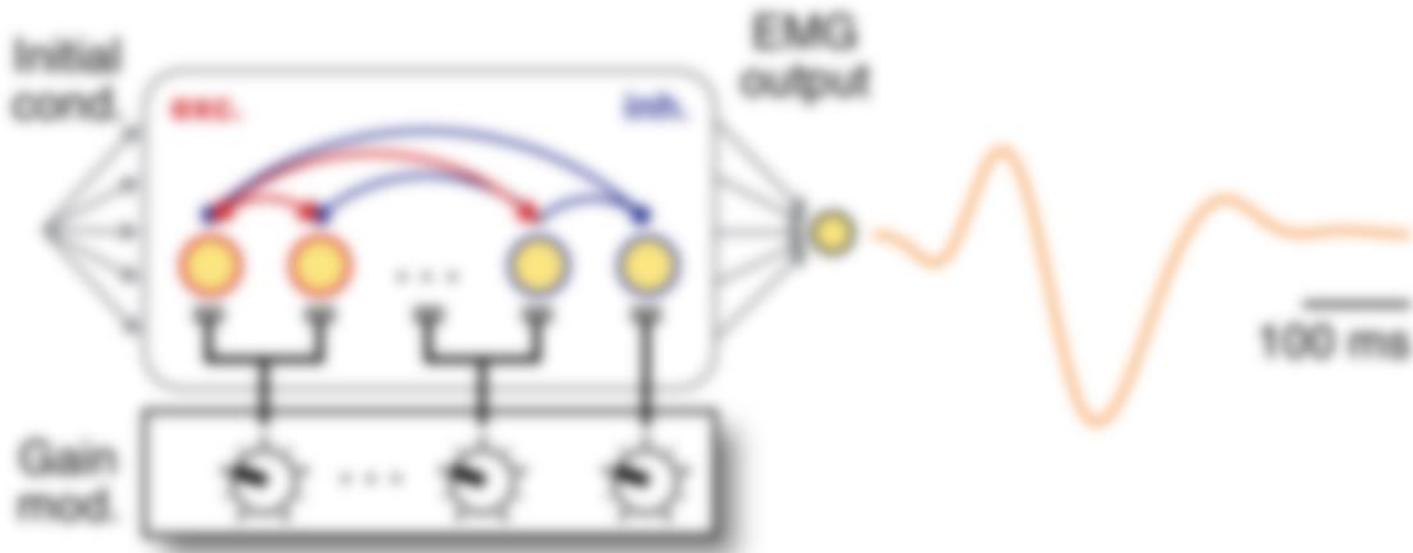
- We can learn gain patterns that generate target output activity.
- Coarse-grained control of neuronal gains provides sufficient flexibility for learning.



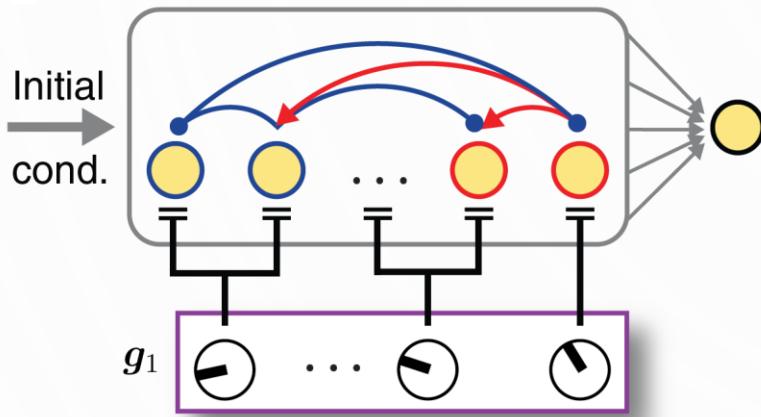
What I have shown so far

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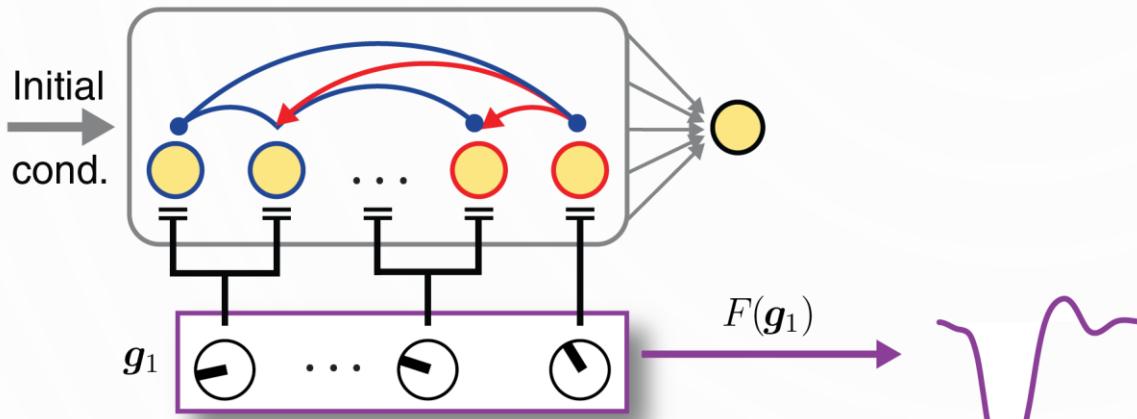
Can previously learned gain patterns be used to rapidly generate new movements?



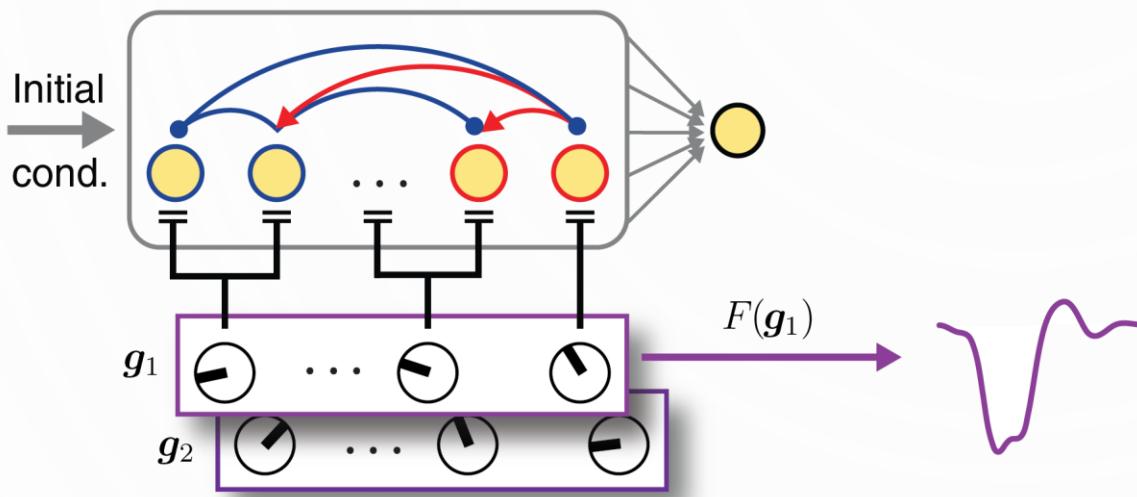
Gain patterns as motor primitives



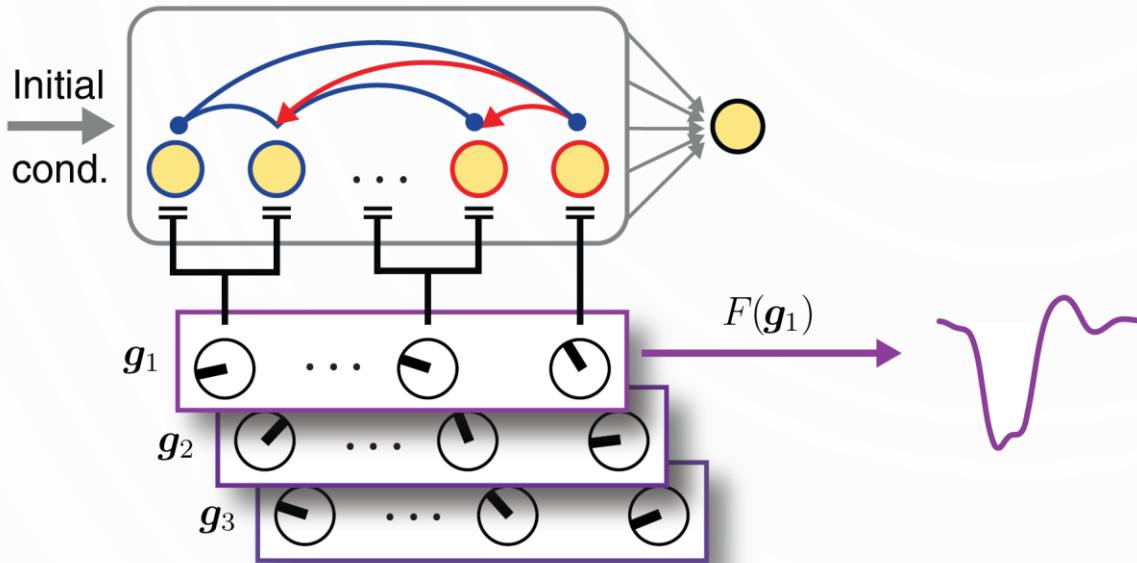
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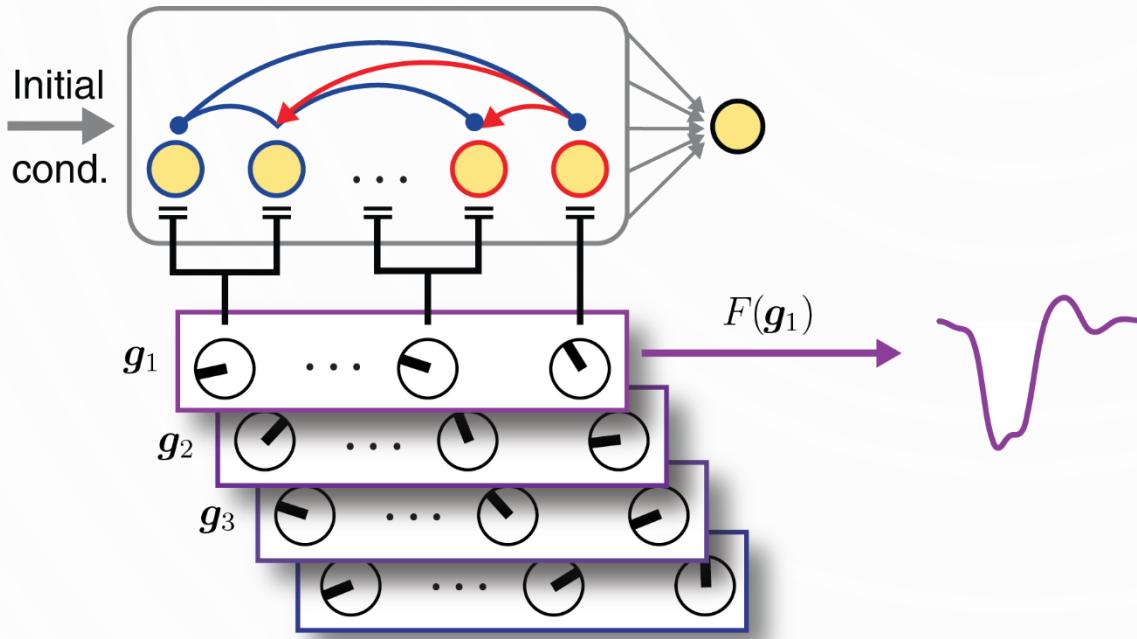
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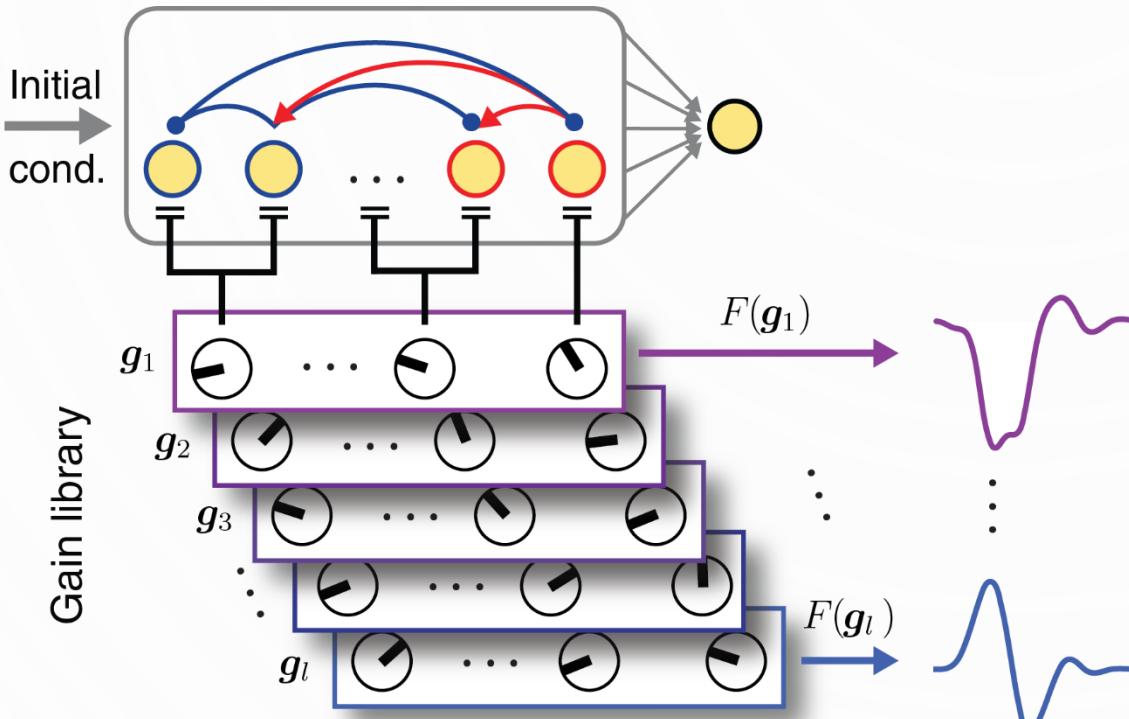
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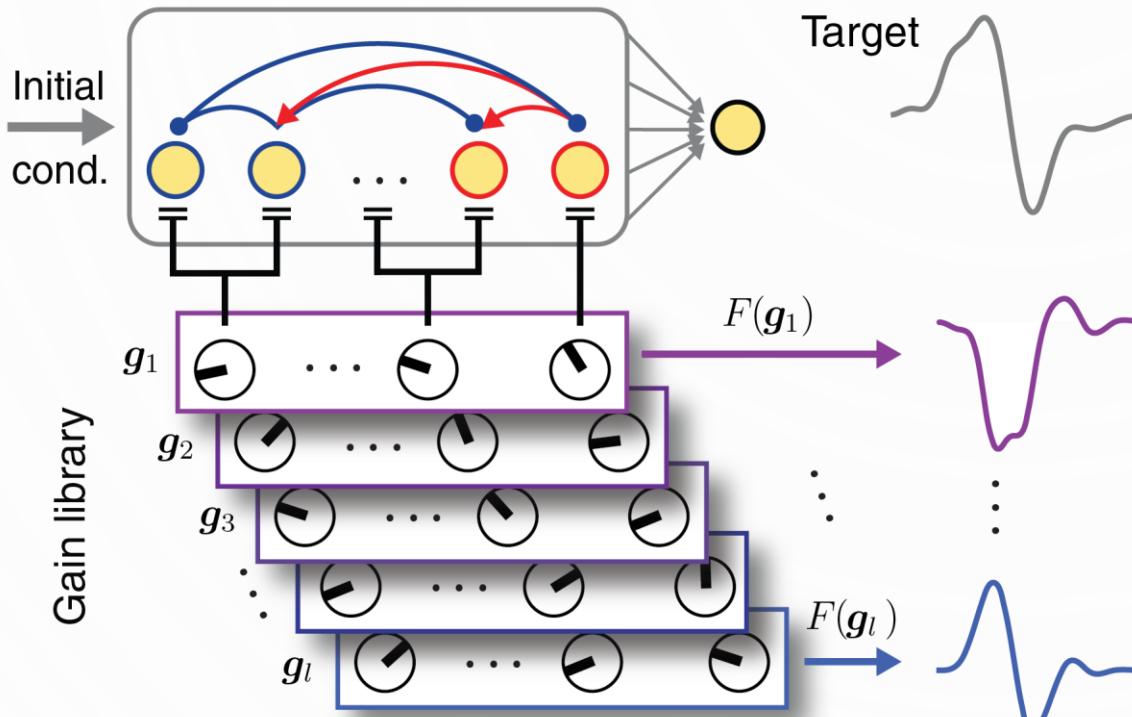
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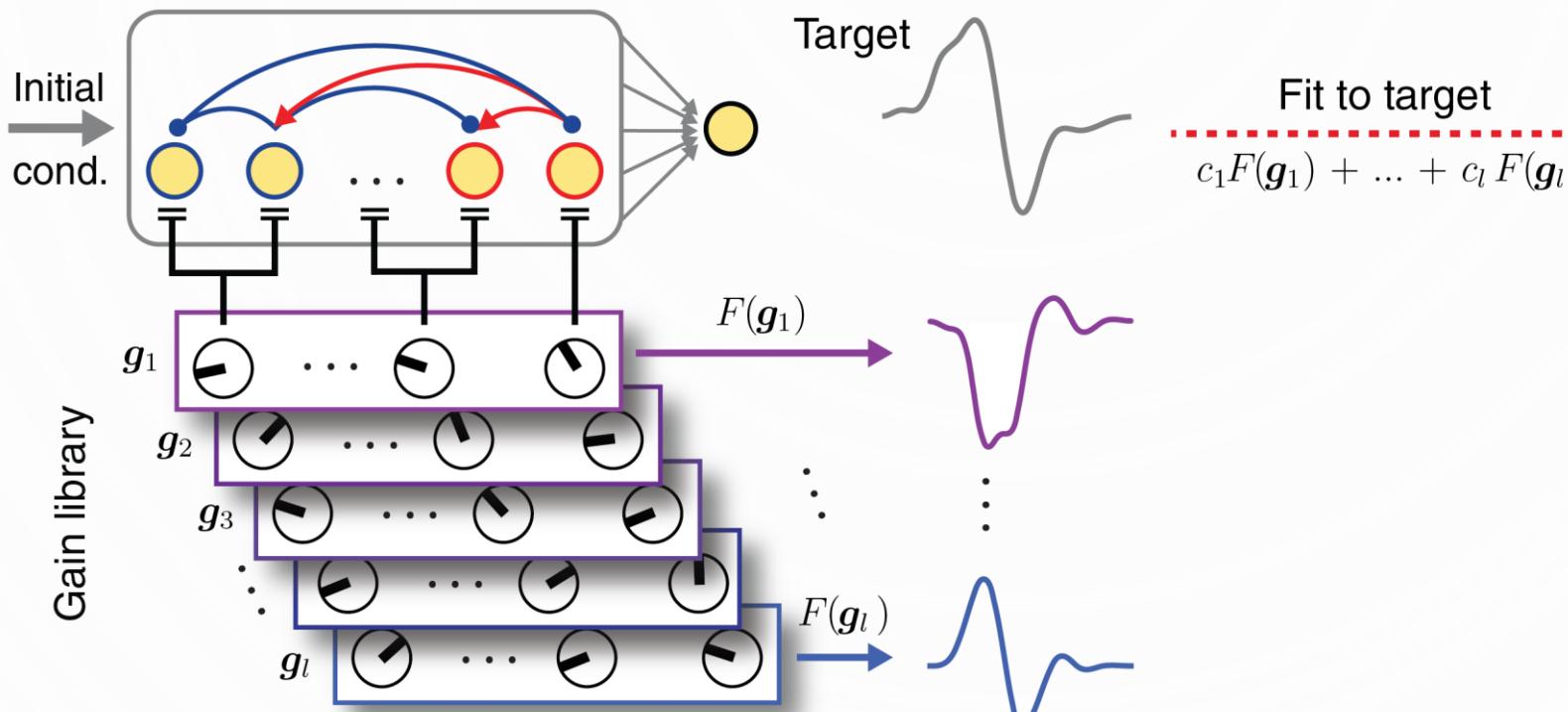
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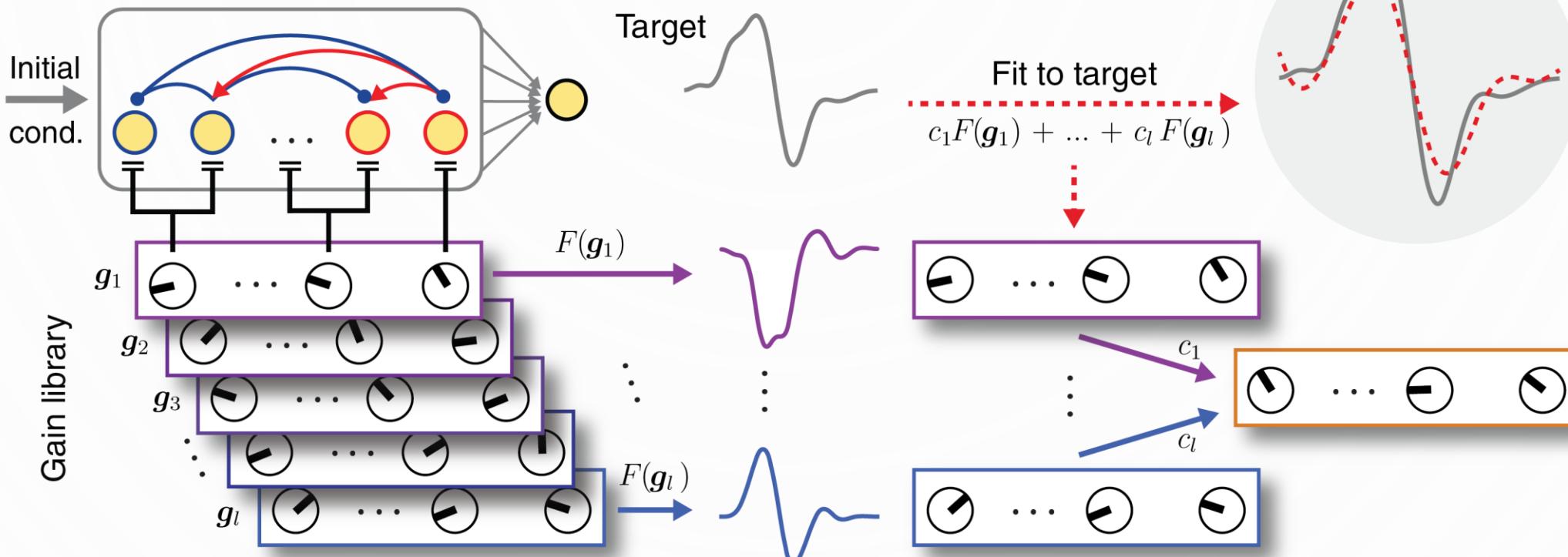


Gain patterns as motor primitives

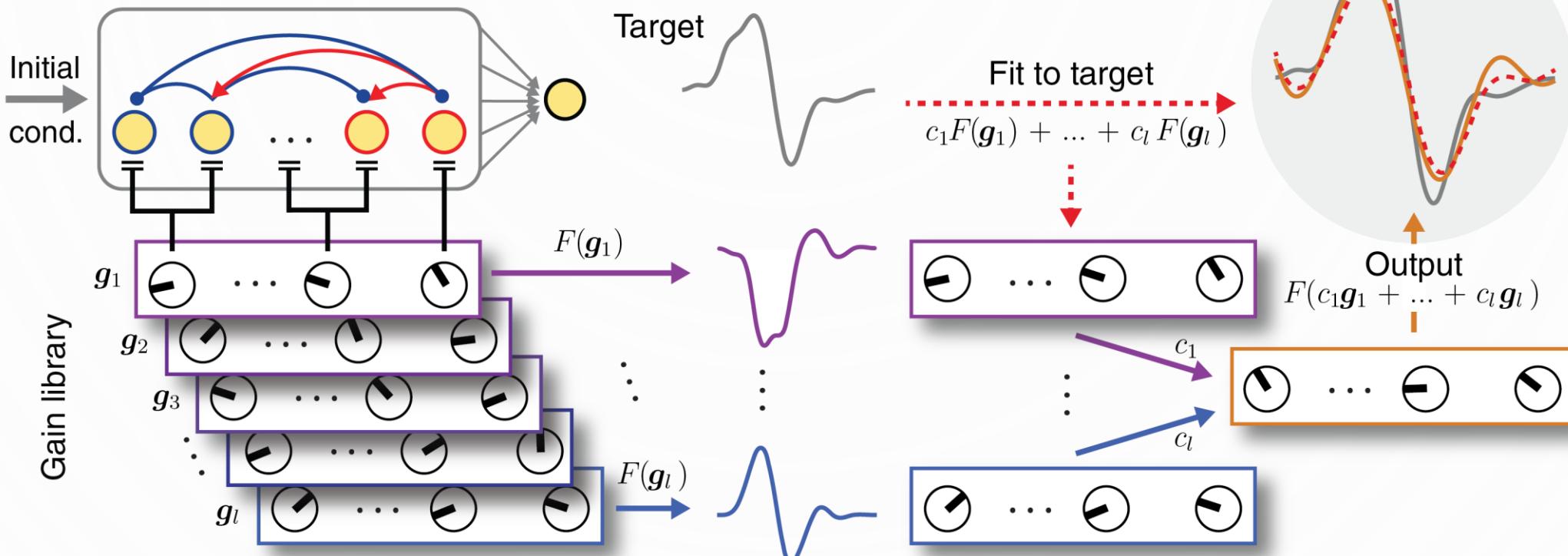


$$c_1 F(\mathbf{g}_1) + \dots + c_l F(\mathbf{g}_l)$$

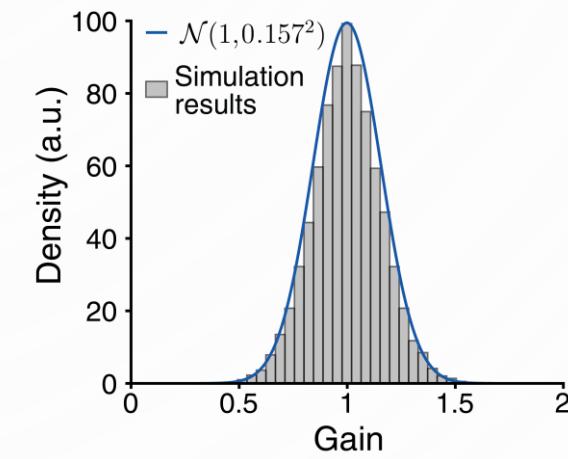
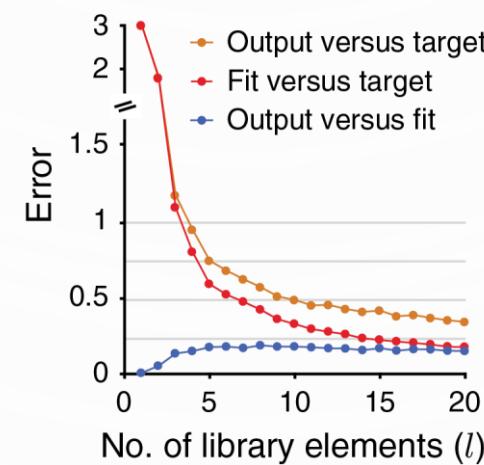
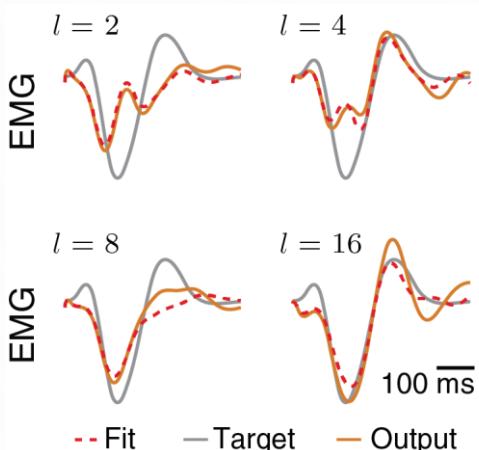
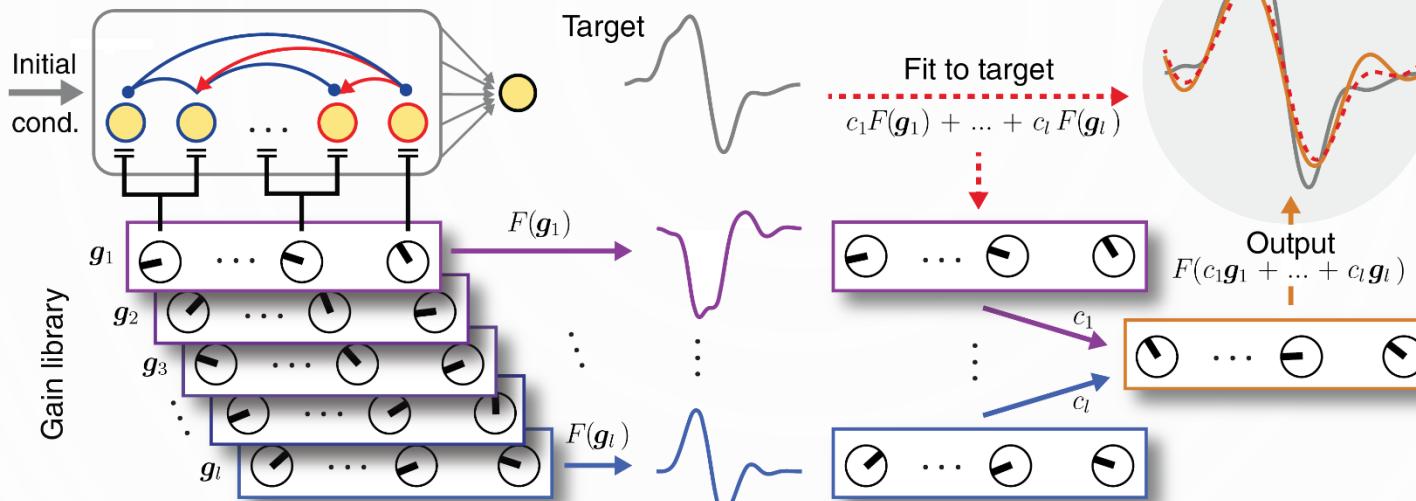
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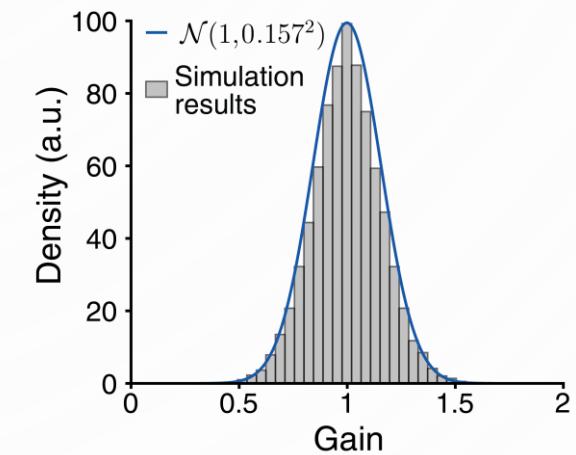
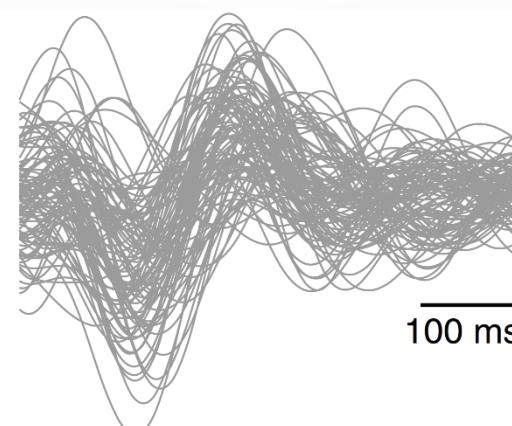
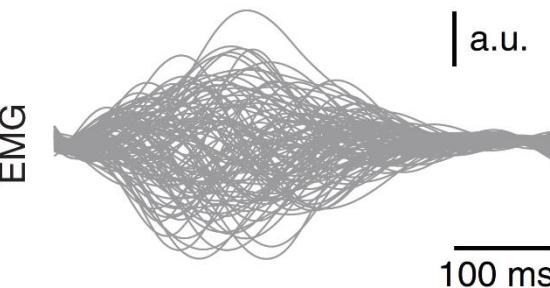
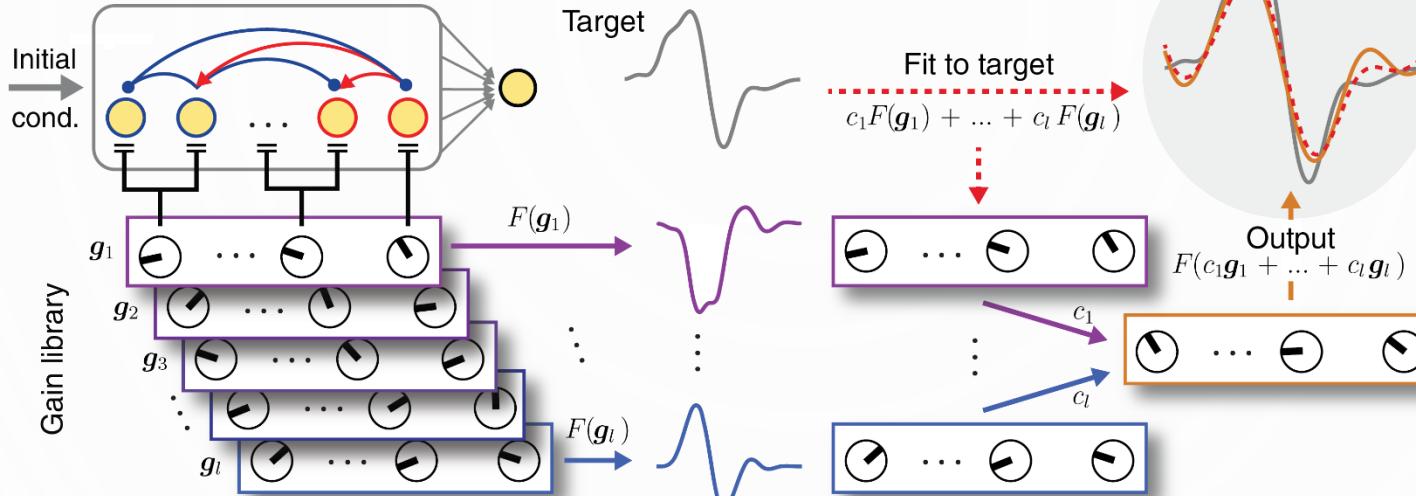
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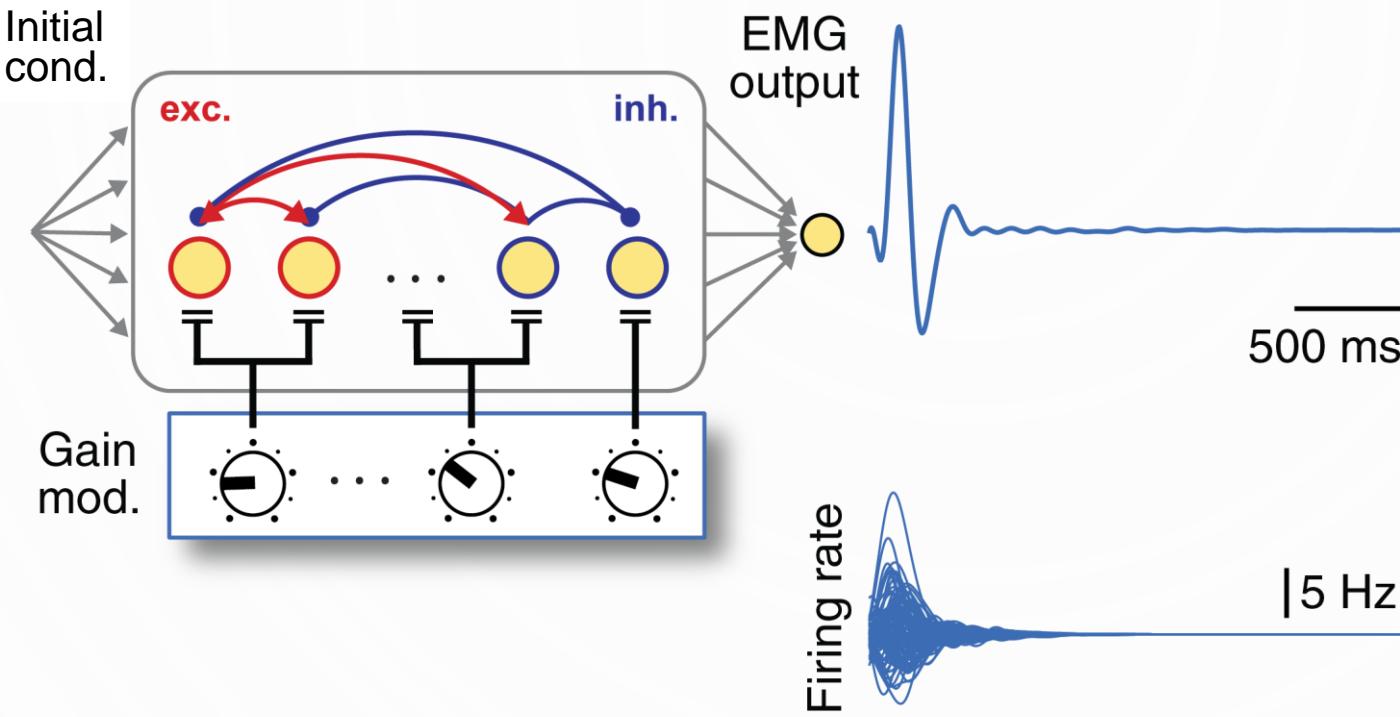
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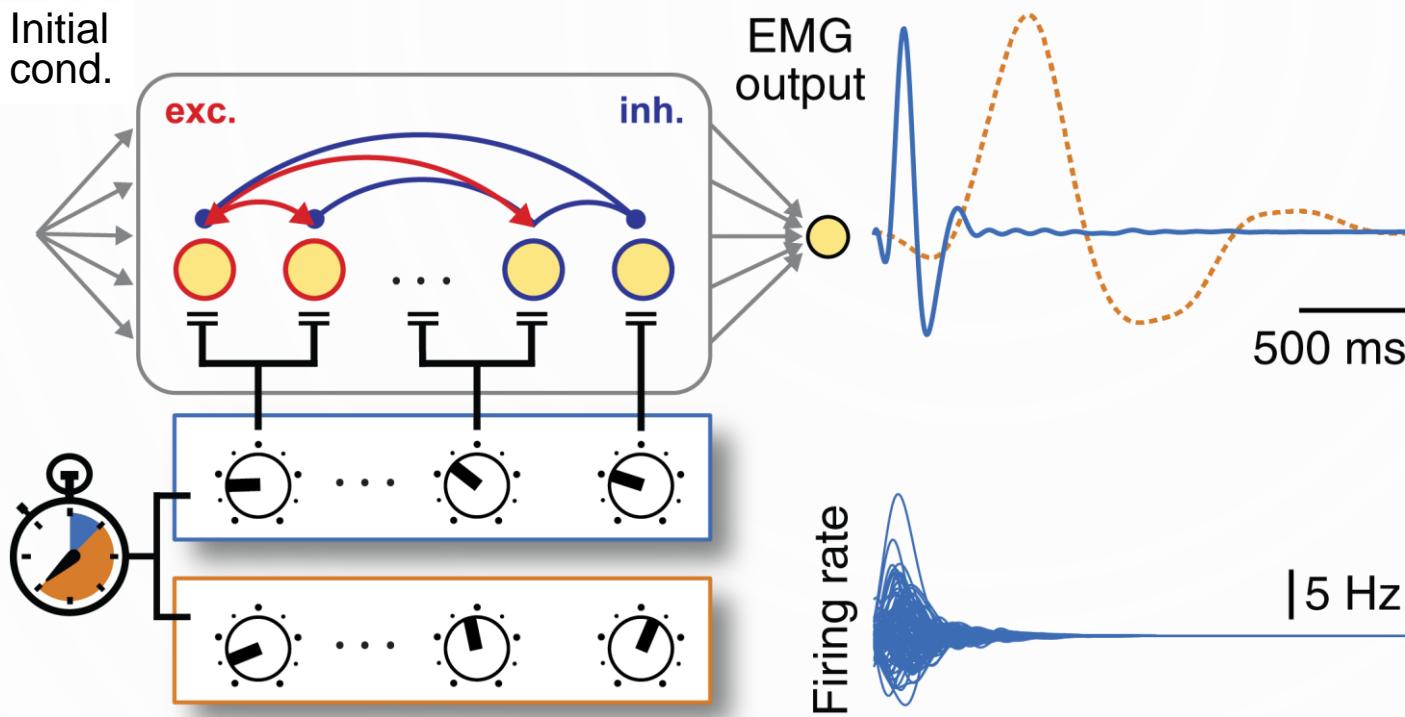
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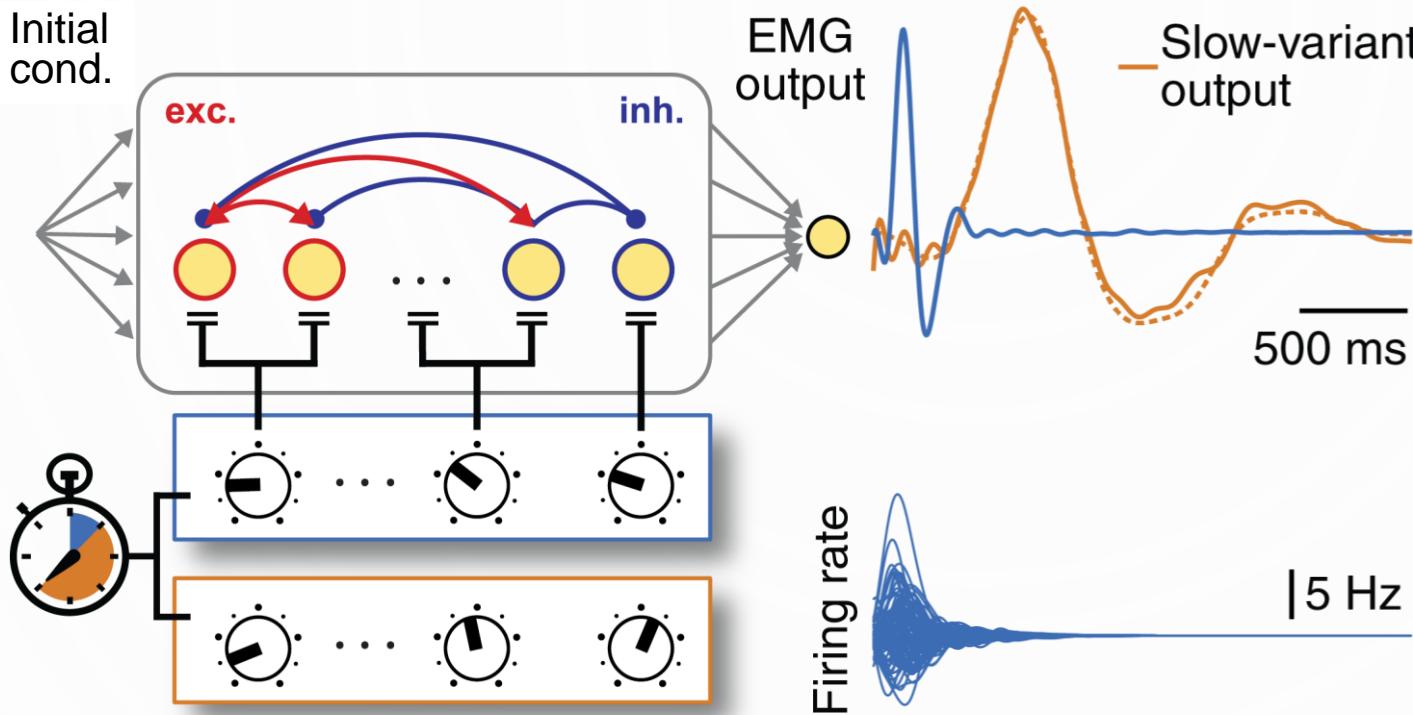
Gain modulation can control movement speed



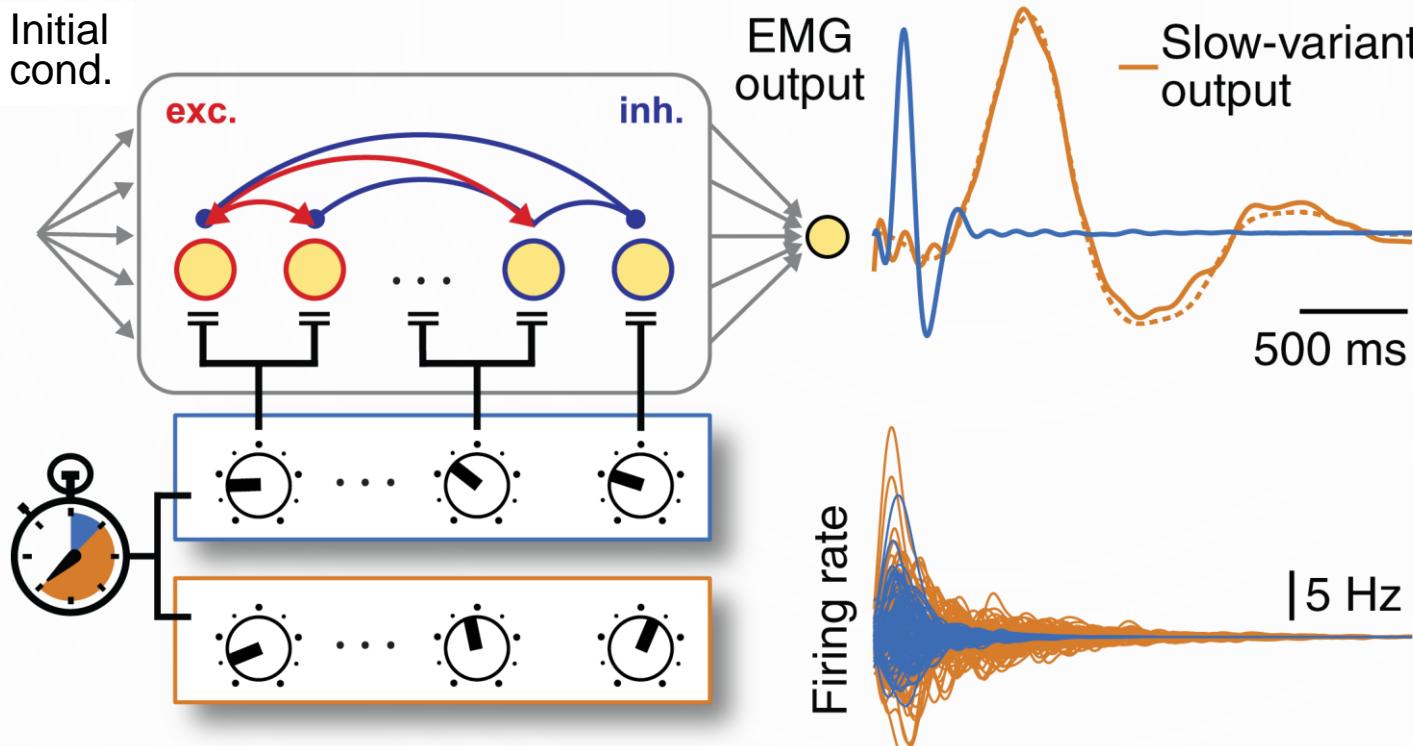
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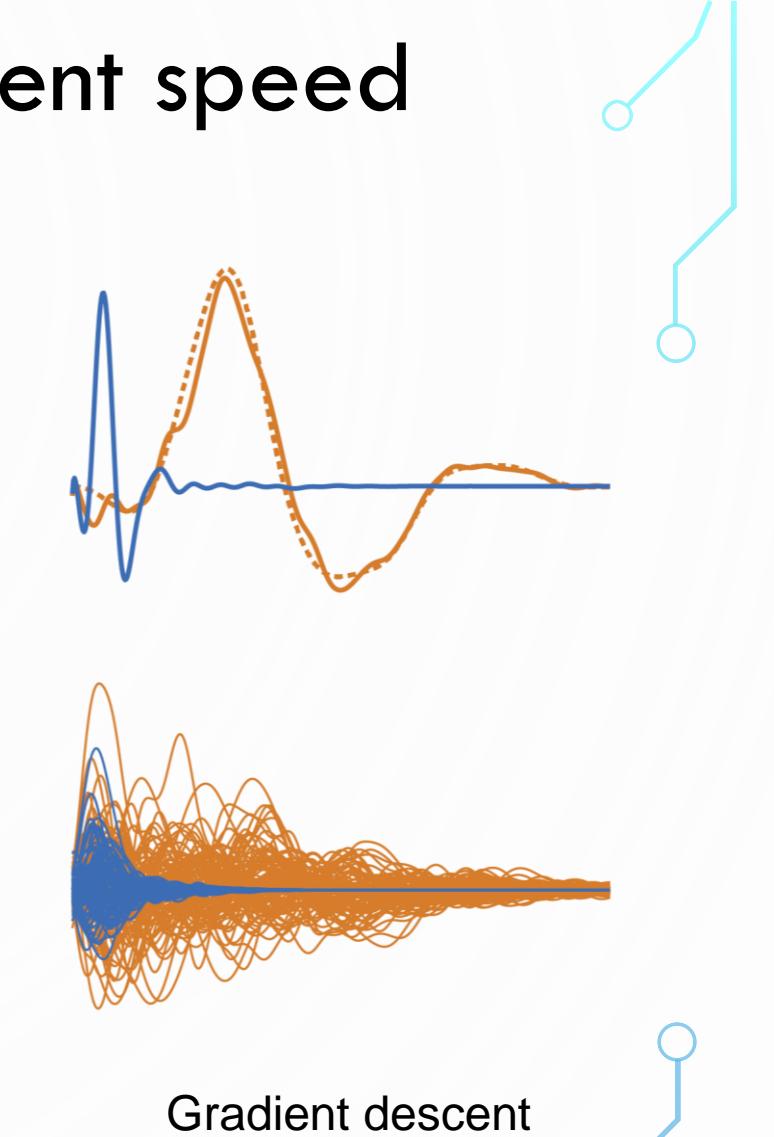
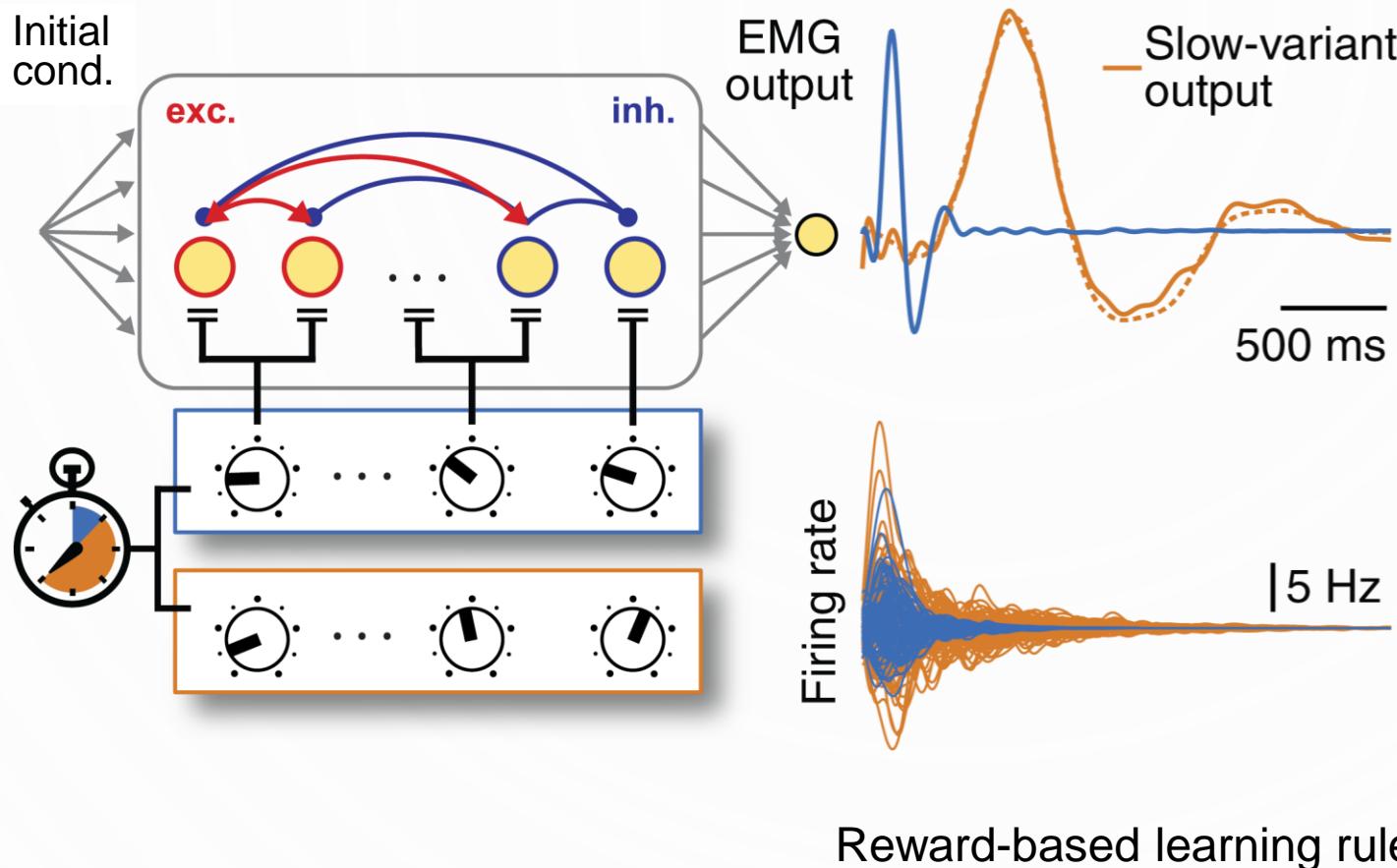
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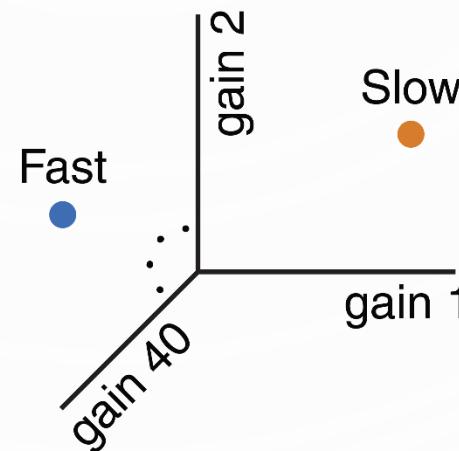
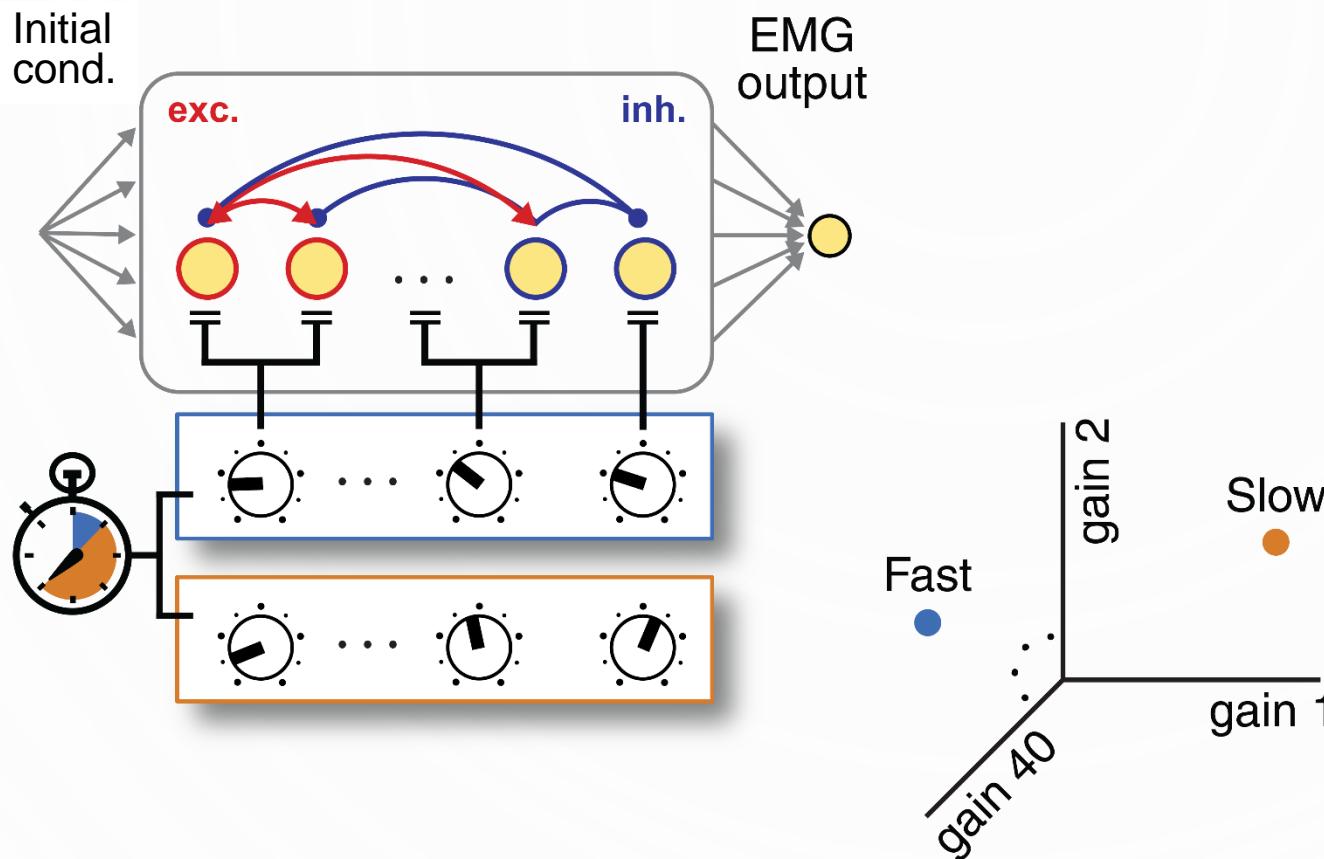
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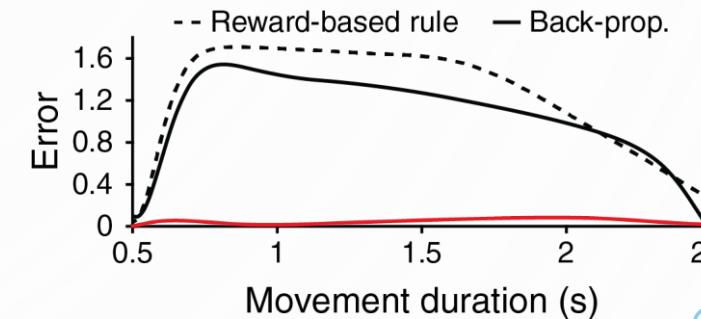
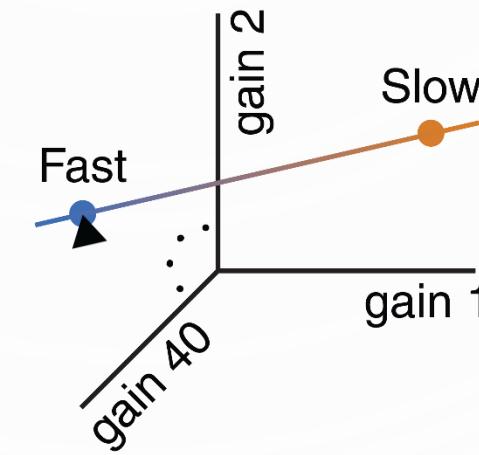
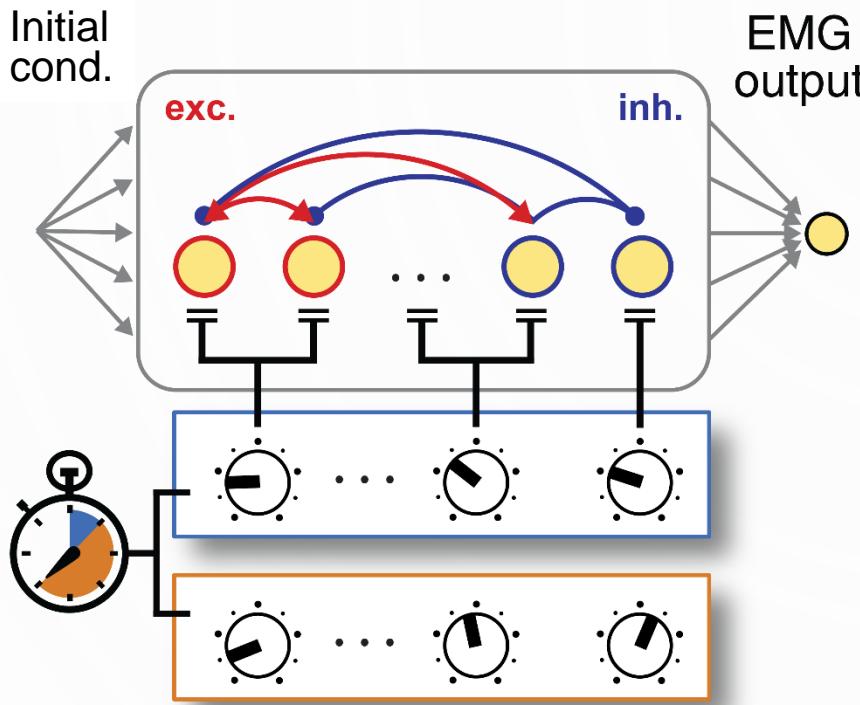
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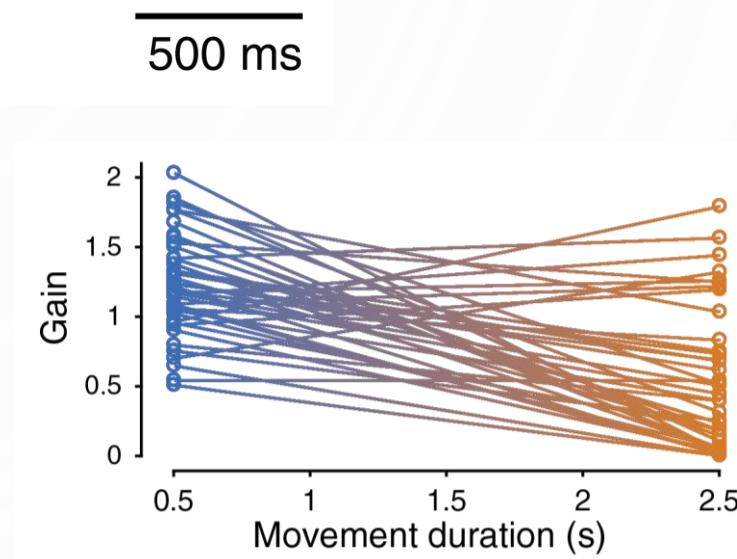
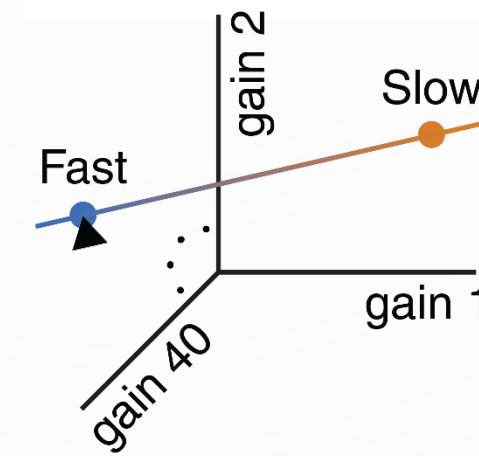
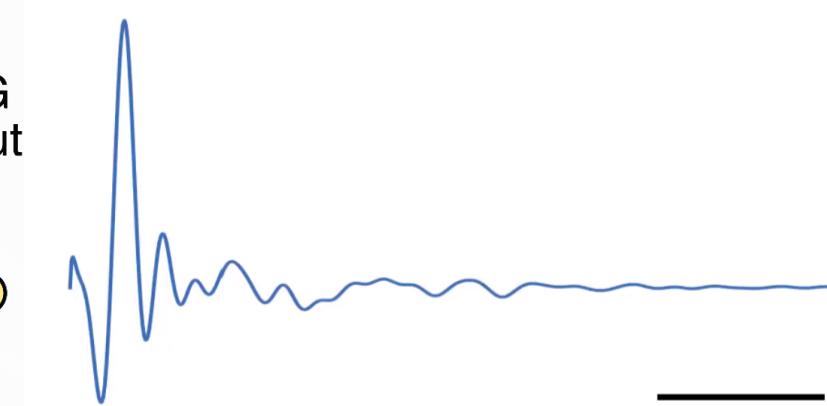
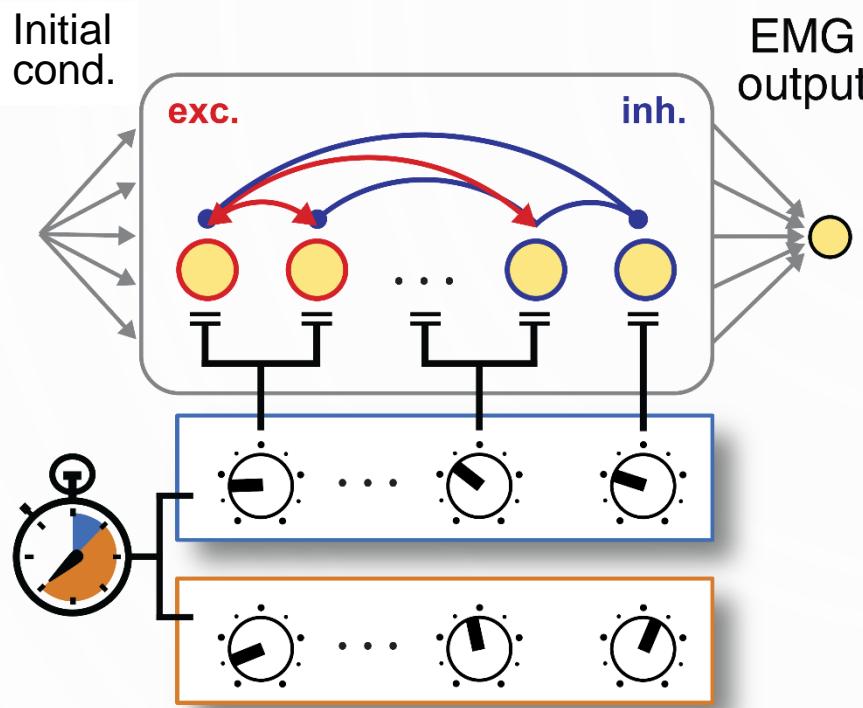
Gain modulation can control movement speed



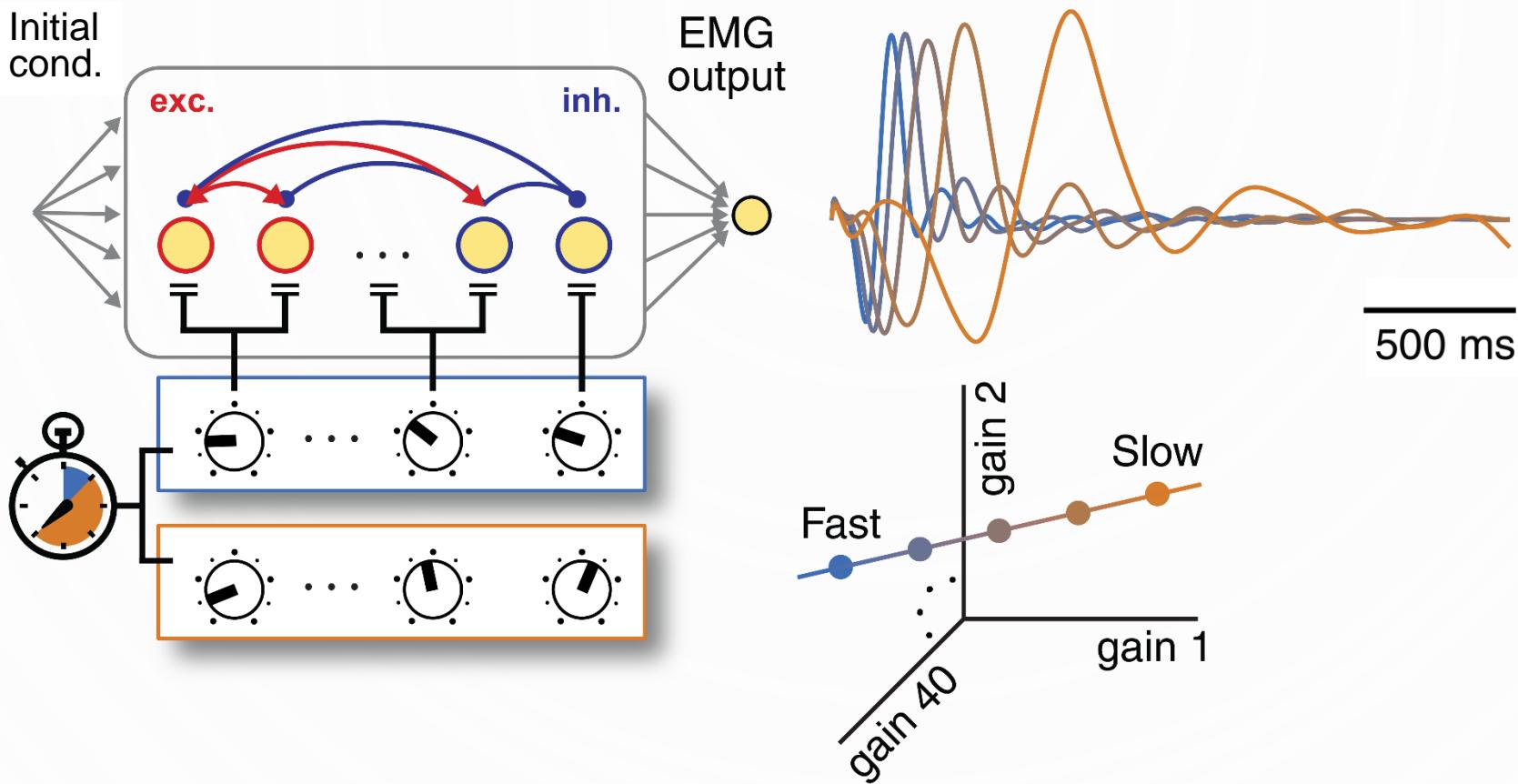
Gain modulation can control movement speed



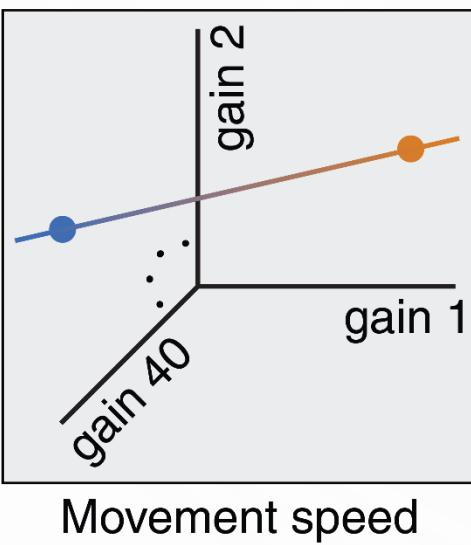
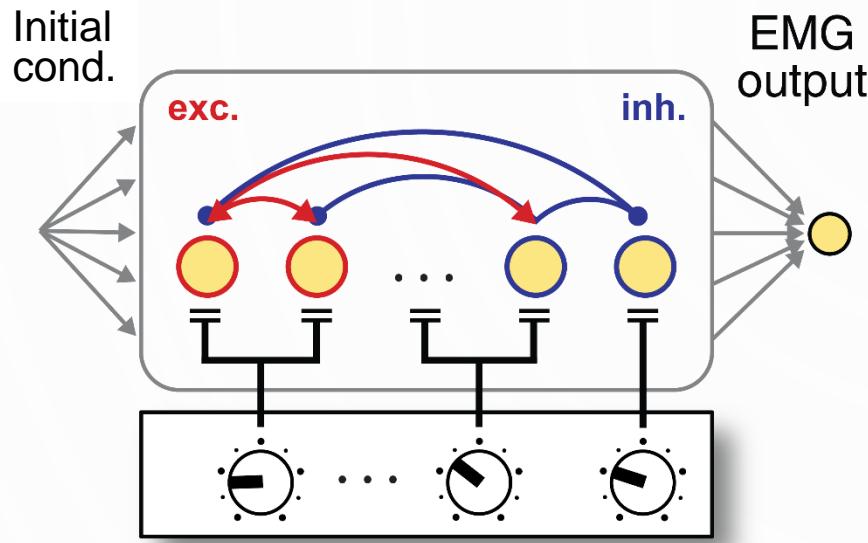
Gain modulation can control movement speed



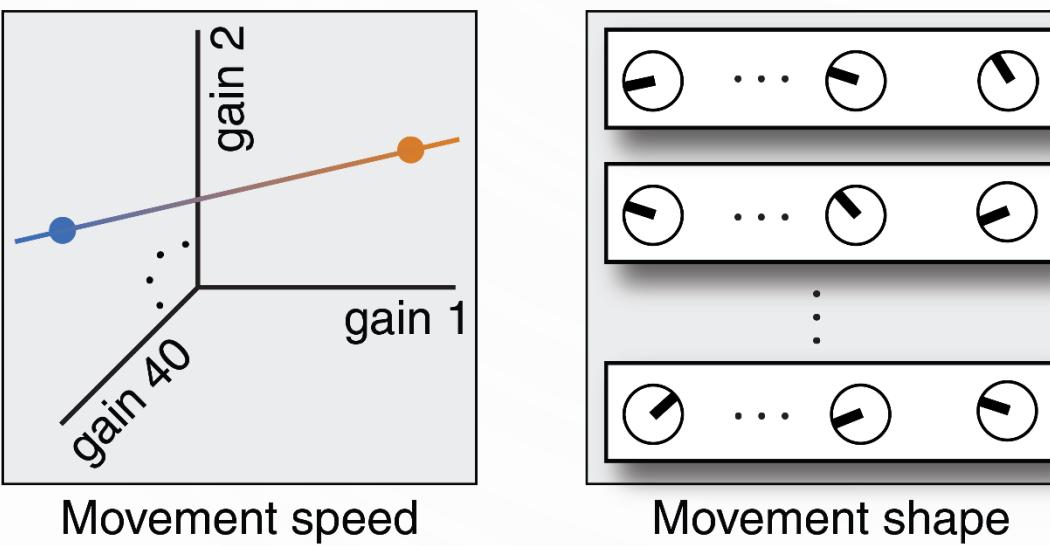
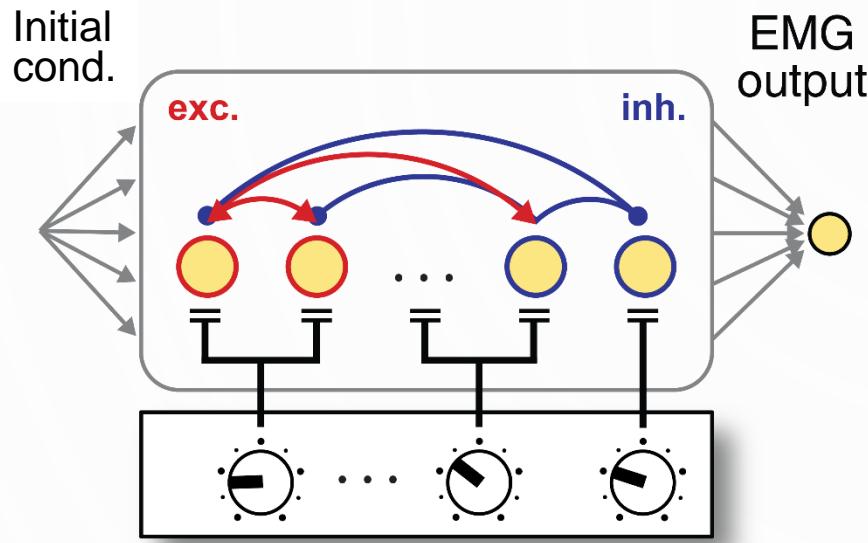
Gain modulation can control movement speed



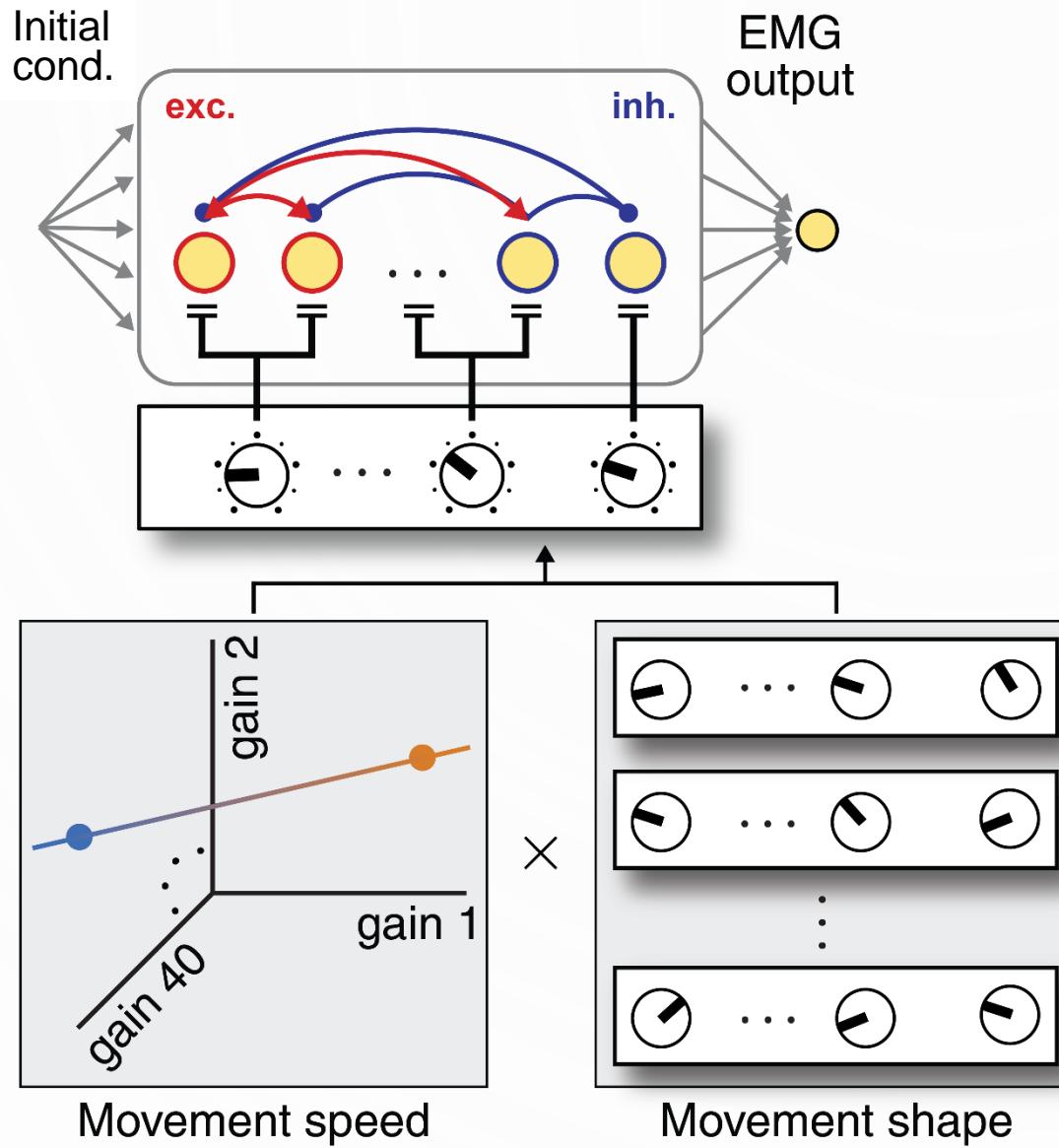
Joint control of movement shape and speed



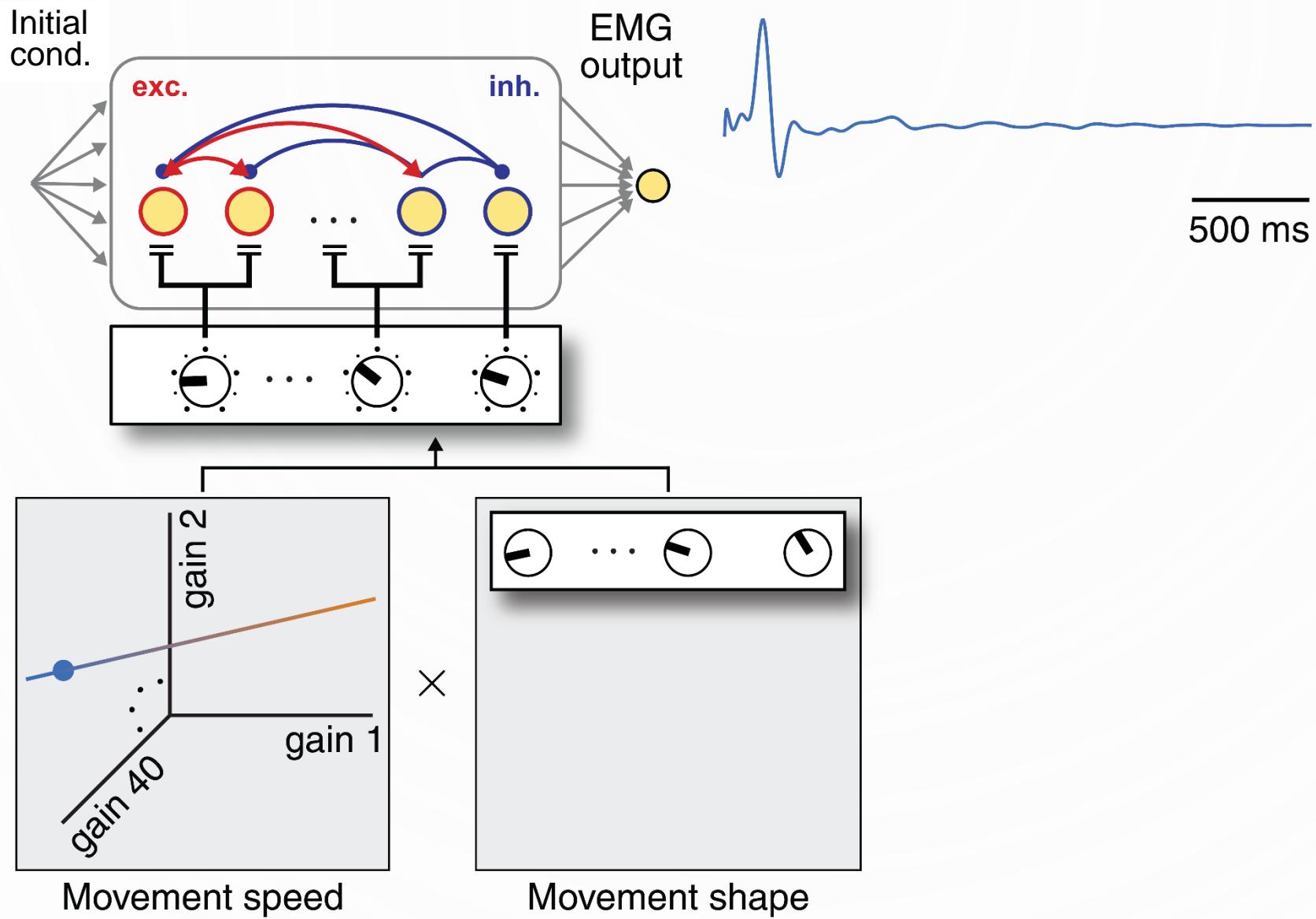
Joint control of movement shape and speed



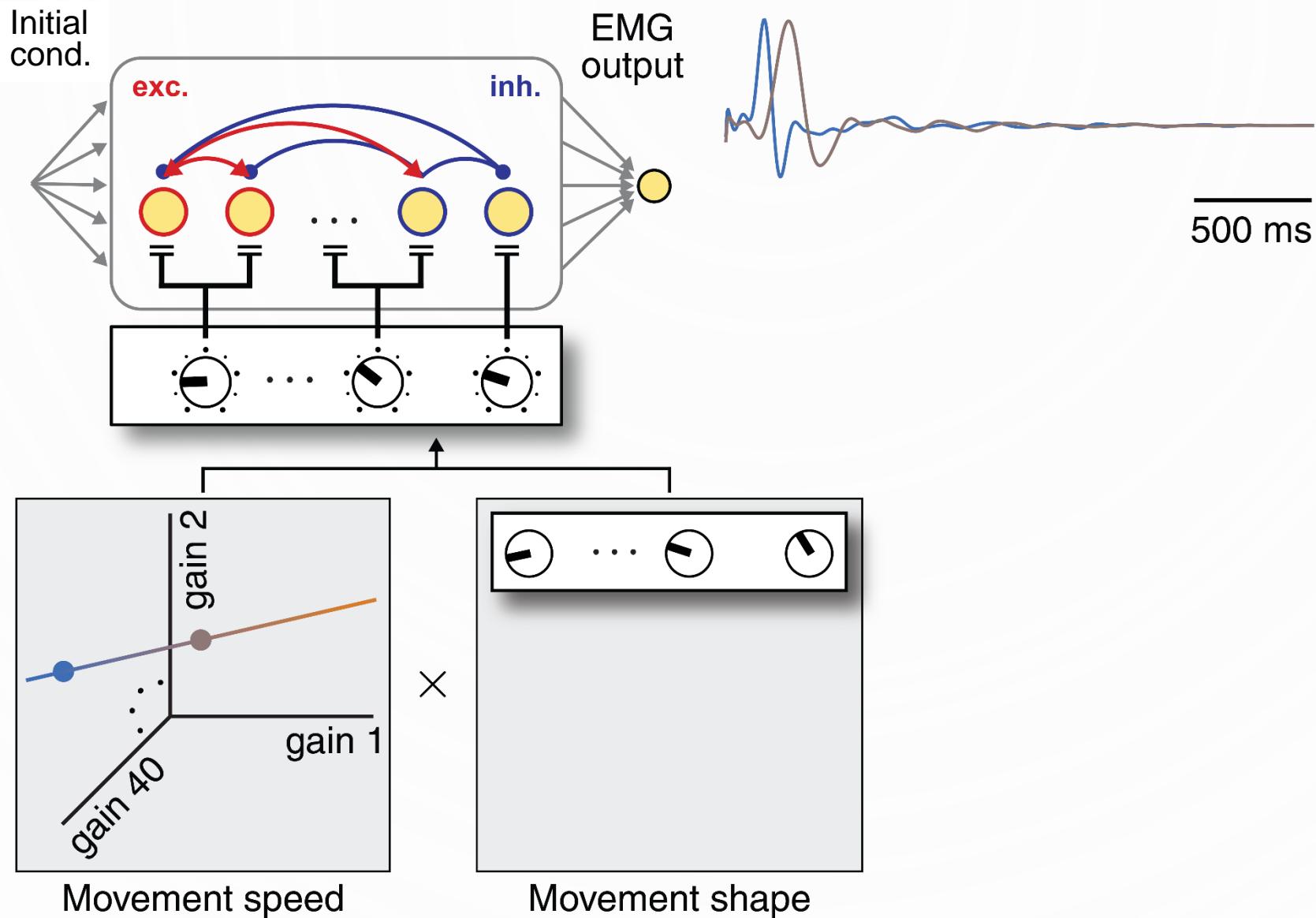
Joint control of movement shape and speed



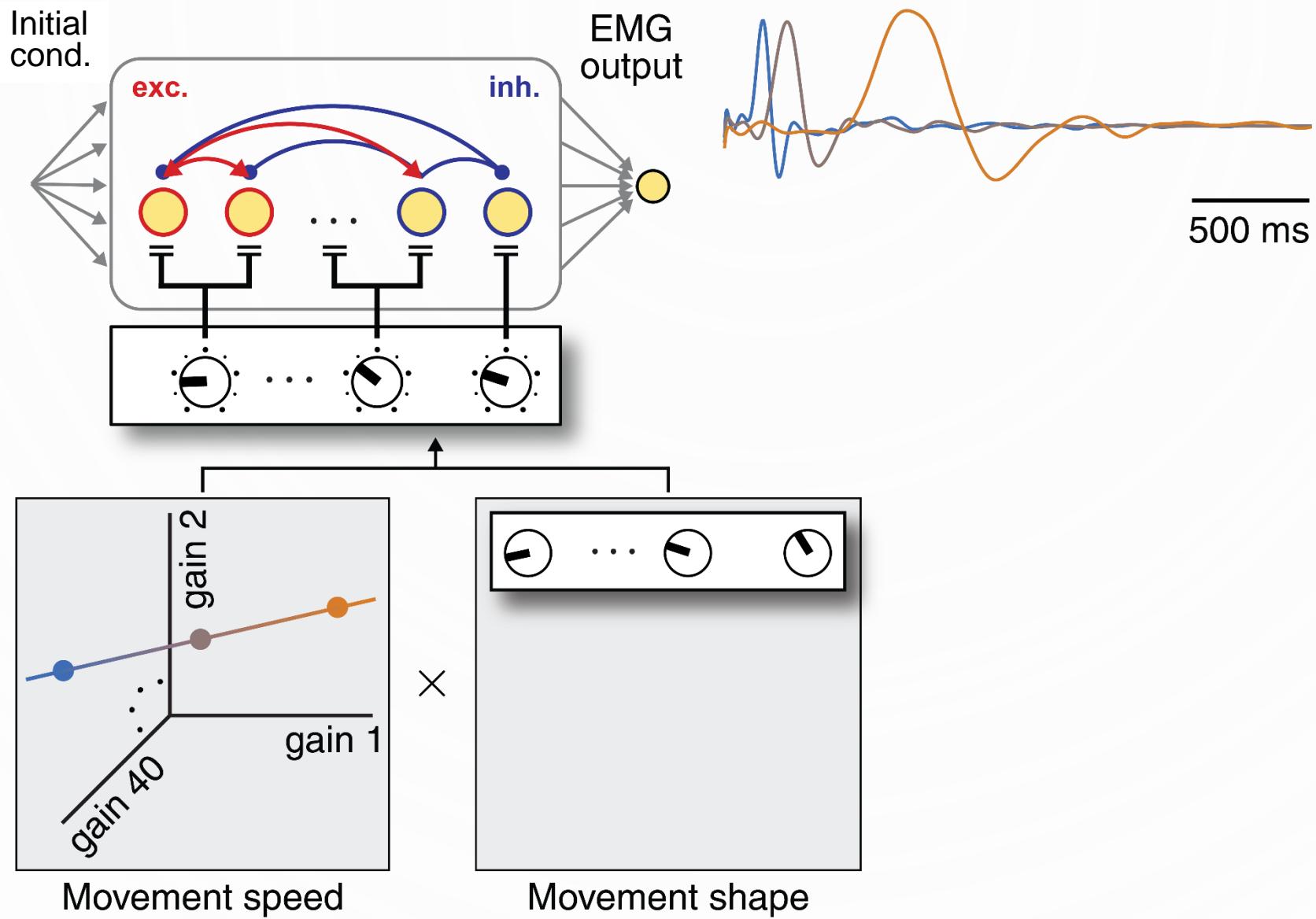
Joint control of movement shape and speed



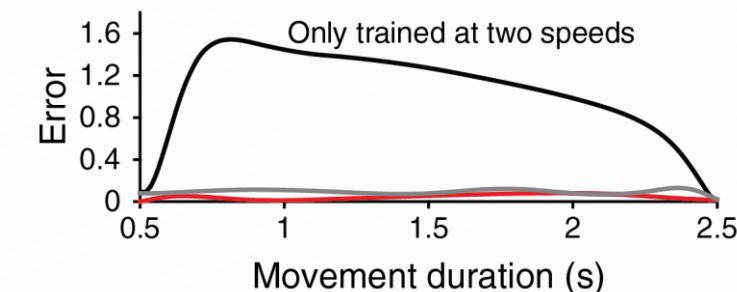
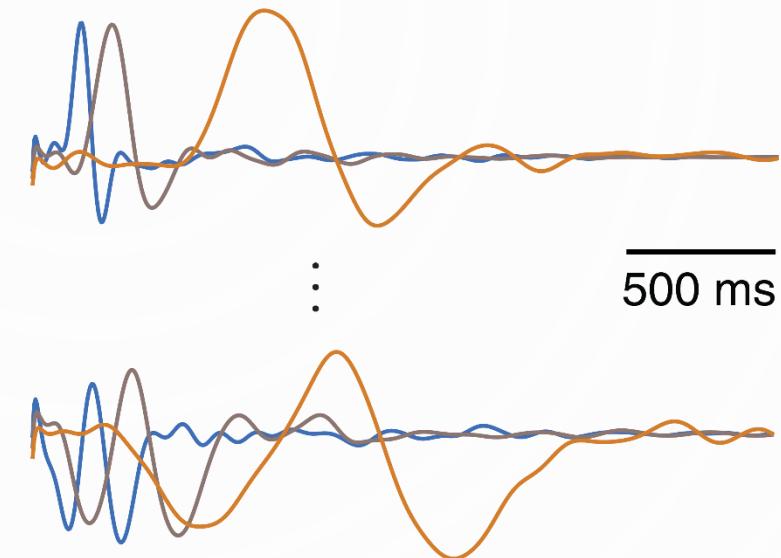
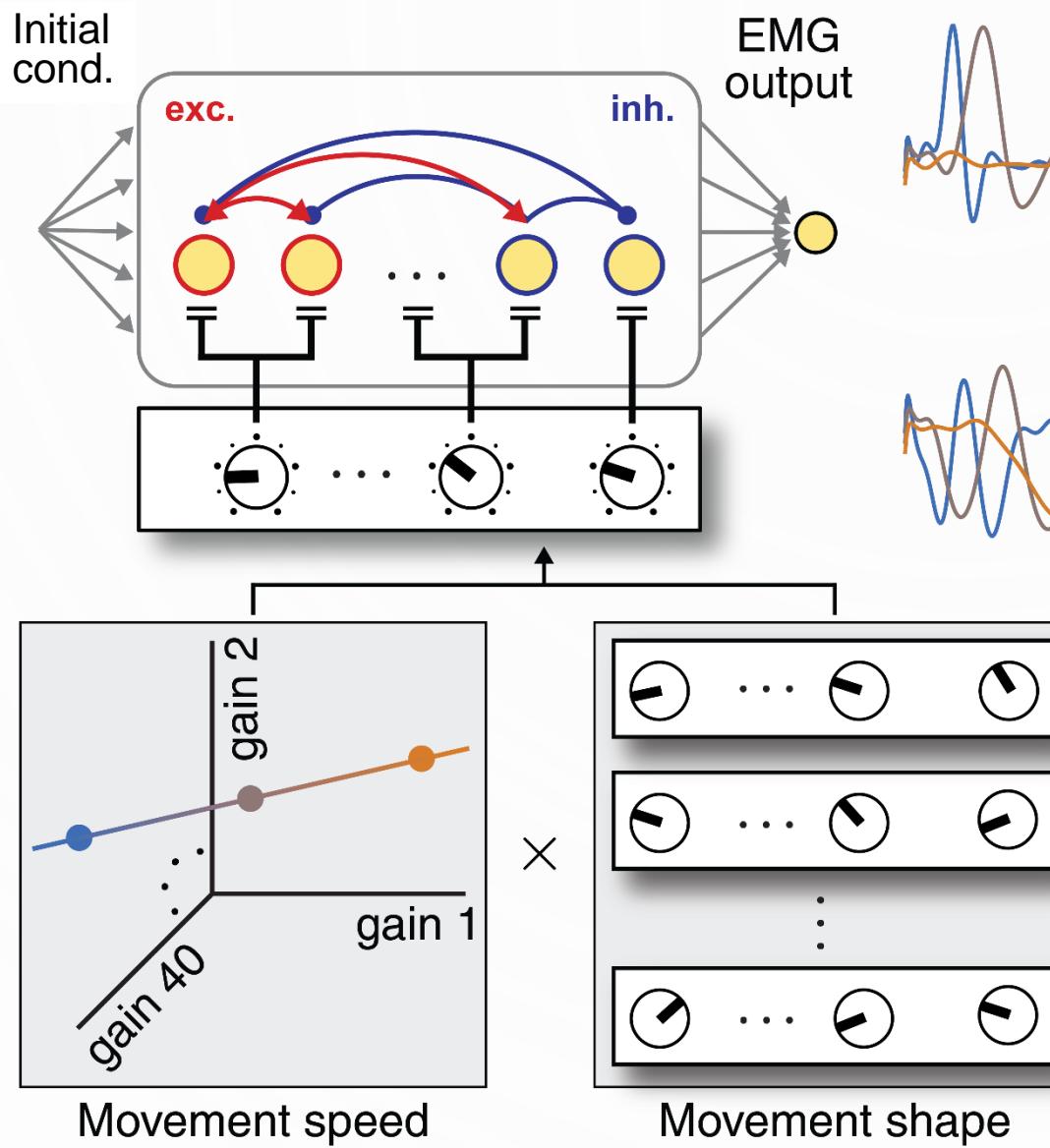
Joint control of movement shape and speed



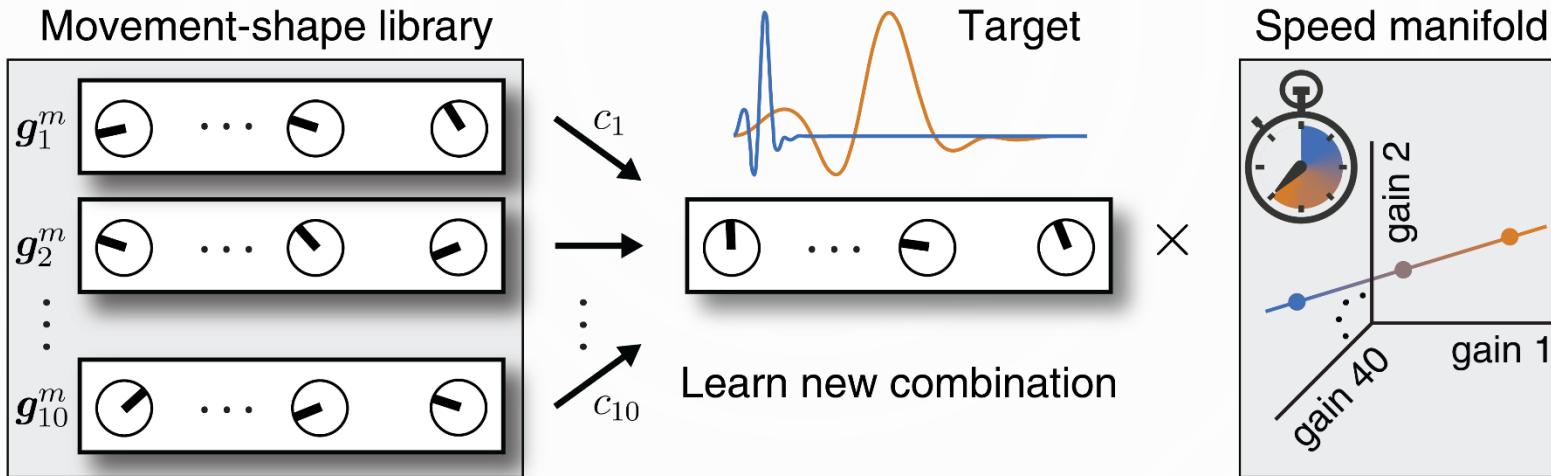
Joint control of movement shape and speed



Joint control of movement shape and speed

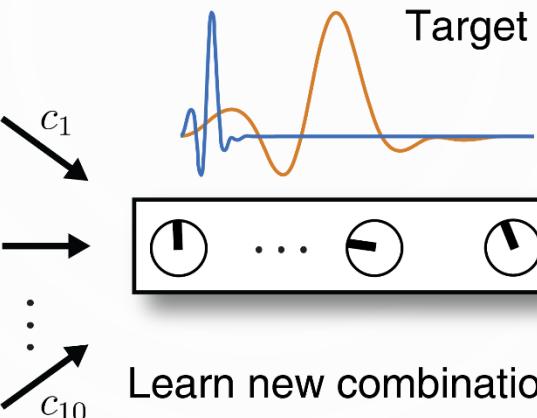
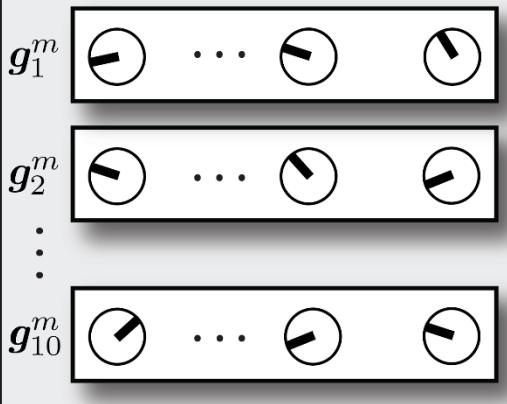


Motor primitives for movement shape and speed

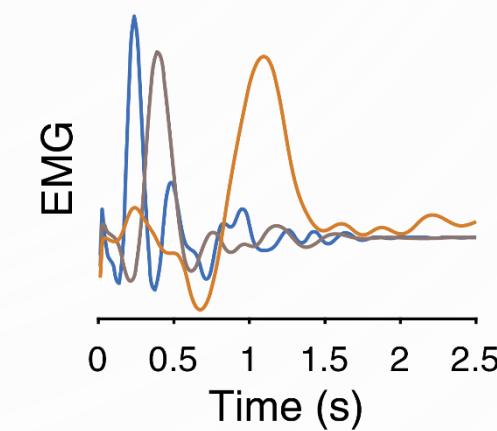
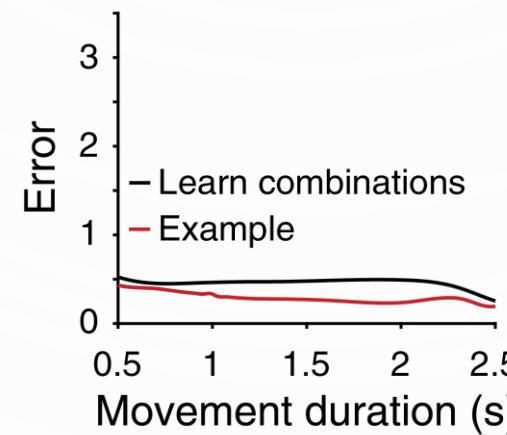
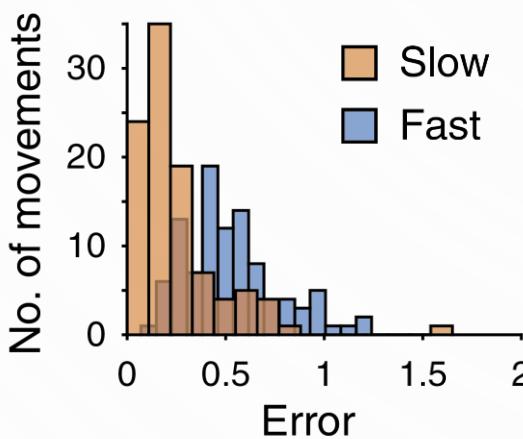
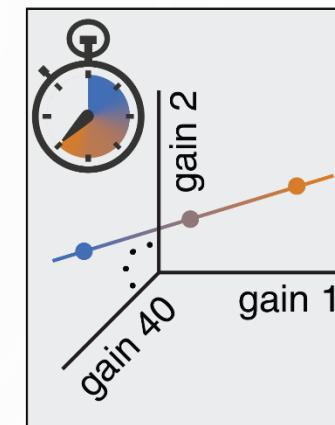


Motor primitives for movement shape and speed

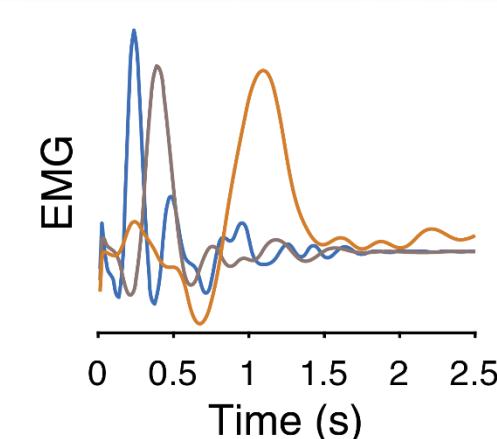
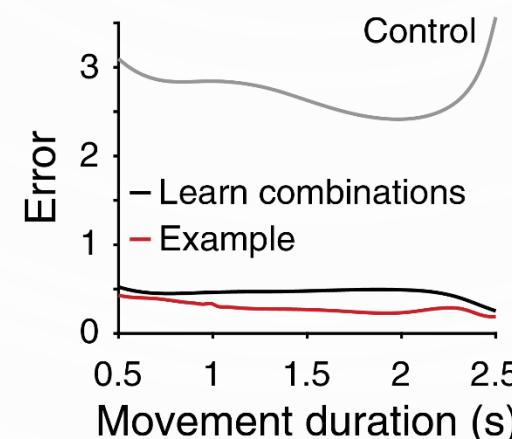
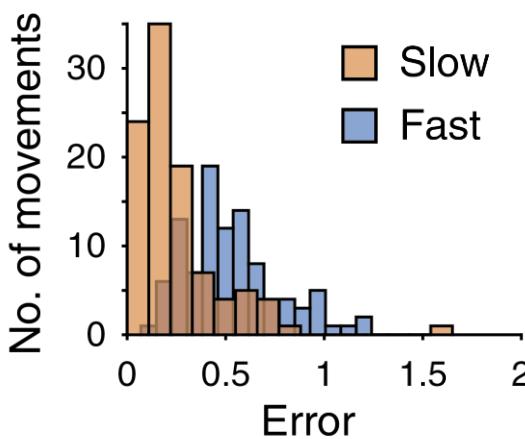
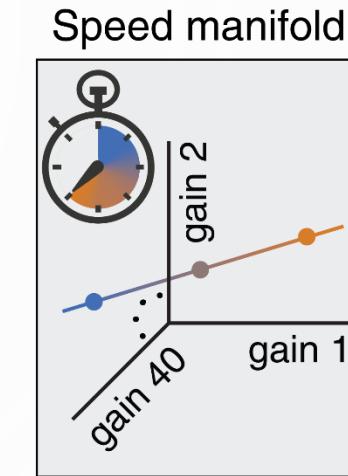
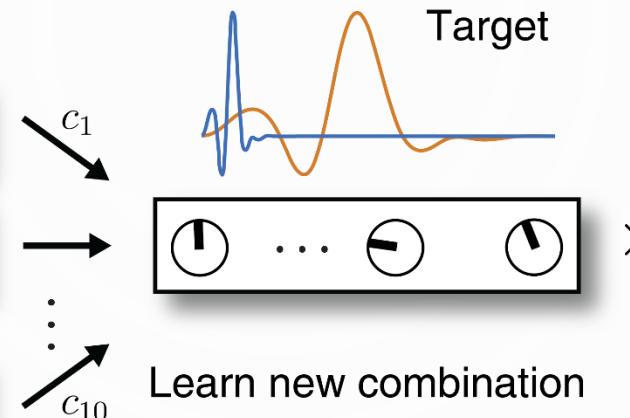
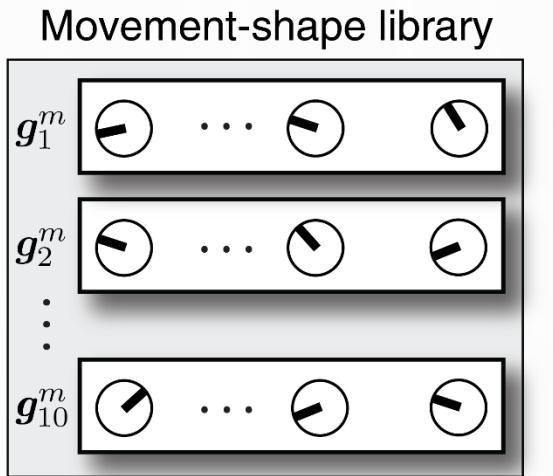
Movement-shape library



Speed manifold



Motor primitives for movement shape and speed



Relationship to other work and outlook

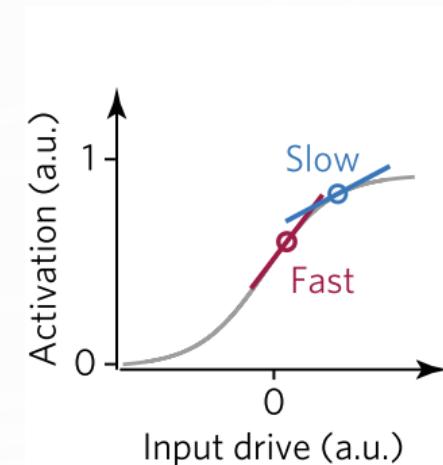
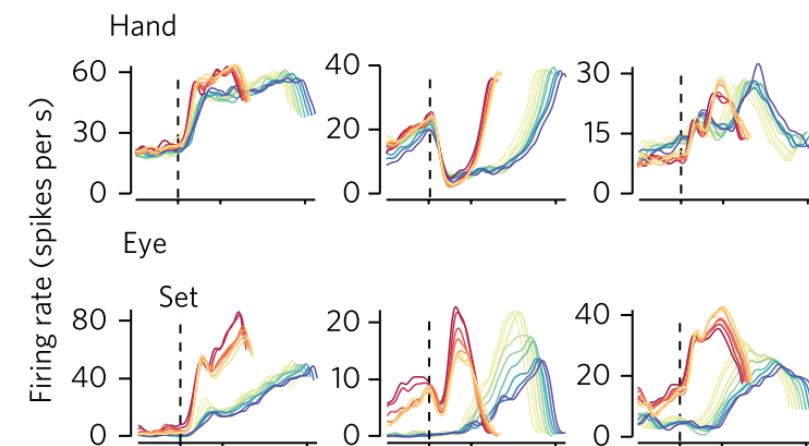
ARTICLES

<https://doi.org/10.1038/s41593-017-0028-6>

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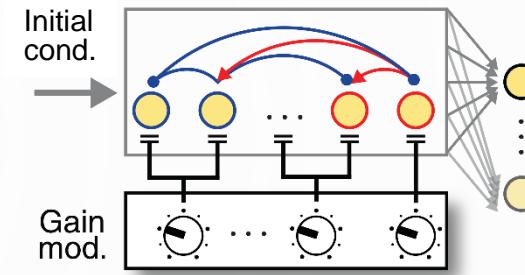
Flexible timing by temporal scaling of cortical responses

Jing Wang^{1,5}, Devika Narain^{1,2,3,4}, Eghbal A. Hosseini^{2,5} and Mehrdad Jazayeri^{1,2,5*}



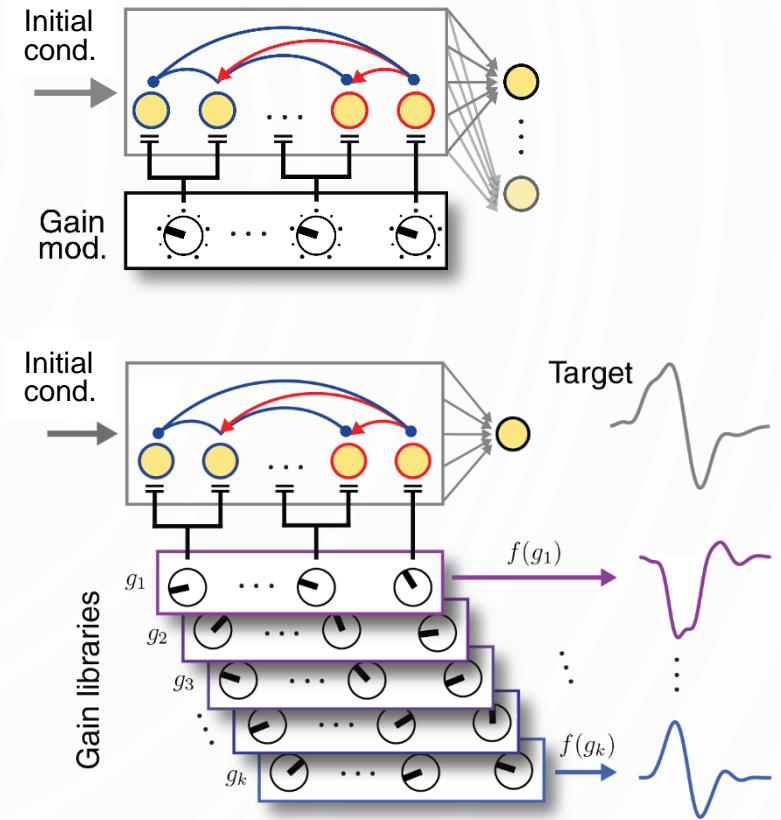
Summary

- A relatively small number of modulatory control units provide sufficient flexibility to adjust neuronal activity on behavioural relevant time scales.



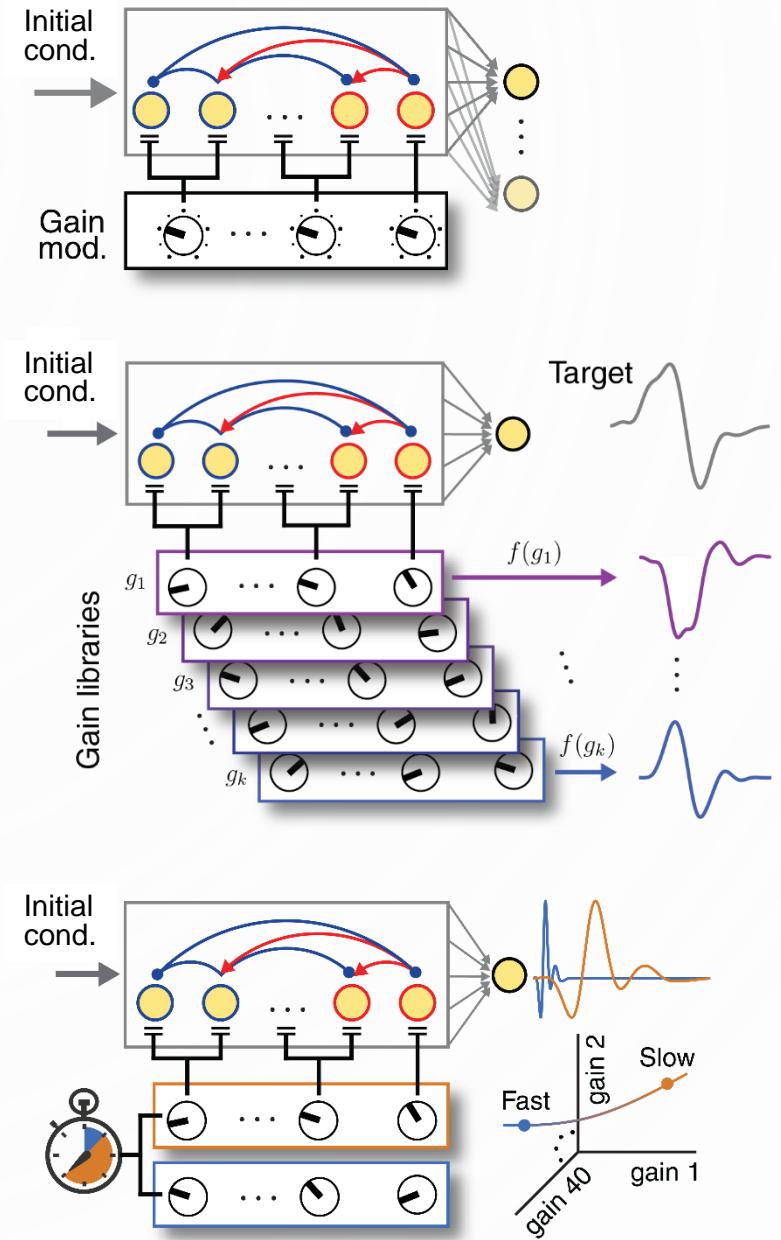
Summary

- A relatively small number of modulatory control units provide sufficient flexibility to adjust neuronal activity on behavioural relevant time scales.
- Previously learned gain patterns can be combined to generate new movements.



Summary

- A relatively small number of modulatory control units provide sufficient flexibility to adjust neuronal activity on behavioural relevant time scales.
- Previously learned gain patterns can be combined to generate new movements.
- We can separately change movement speed while preserving movement shape, thus enabling efficient and independent movement control in space and time.



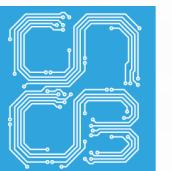
Thanks



Supervised by:

Tim Vogels and Mason Porter

and in collaboration with Guillaume Hennequin



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